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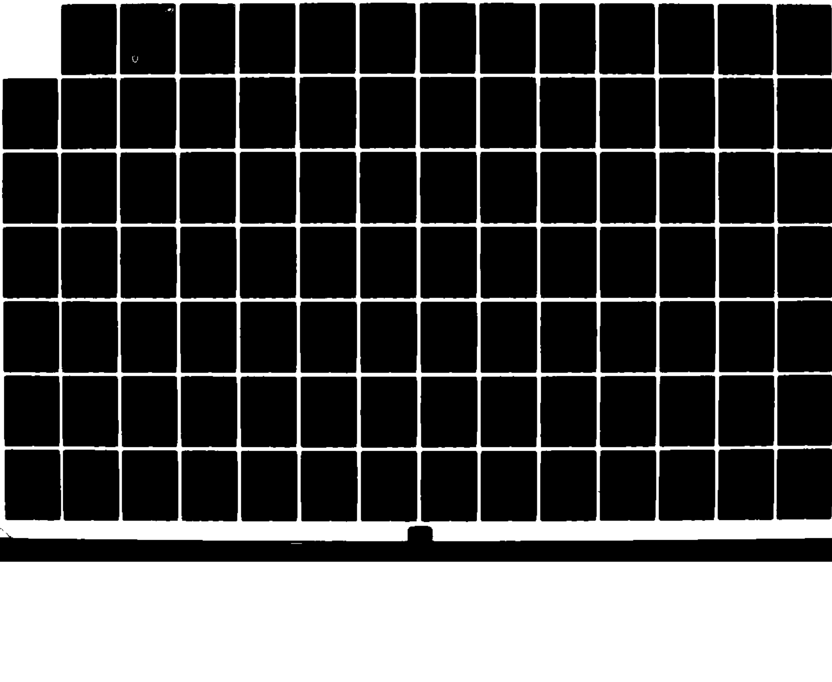

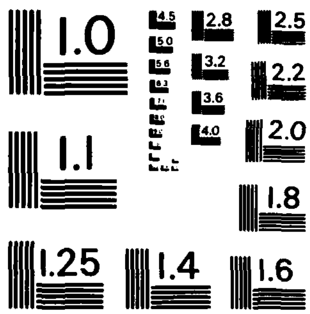

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QUALITY CONTROL AND NONDESTRUCTIVE EVALUATION TECHNIQUES FOR COMPOSITES - PART VI: ACOUSTIC EMISSION - A STATE-OF-THE-ART REVIEW

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DEPARTMENT OF PHYSICS

May 1983

FINAL REPORT

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4. TITLE (and Subtitle) QUALITY CONTROL AND NONDESTRUCTIVE EVALUATION TECHNIQUES FOR COMPOSITES - PART VI: ACOUSTIC EMISSION - A STATE-OF-THE-ART REVIEW		5. TYPE OF REPORT & PERIOD COVERED Final Report 8/5/82 to 2/4/83 6. PERFORMING ORG. REPORT NUMBER Monitoring Agency, TR 83-25
7. AUTHOR(s) M. A. Hamstad		8. CONTRACT OR GRANT NUMBER(s) DAAG29-81-D-0100 TCN 82-229
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Denver Colorado Seminary Denver, CO 80208		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS D/A Project: 1827119 AMCMS Code: 1497.20 Agency Accession: DD S7119(EP2)
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Aviation Research & Development Command ATTN: DRDAV-EGX 4300 Goodfellow Blvd., St. Louis, MO 63120		12. REPORT DATE May 1983 13. NUMBER OF PAGES 307
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Army Materials and Mechanics Research Center ATTN: DRXMR-K Watertown, Massachusetts 02172		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION DOWNGRADING SCHEDULE

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Composite materials, Quality assurance, Quality control, Nondestructive testing, Acoustic emissions, Damage, Defects (materials), State-of-the-art

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ABSTRACT

A comprehensive report on the subject of acoustic emission (AE) as applied to characterization and testing of composite materials and structures has been written. First, an extensive bibliography of over 300 references of the literature in this field is presented. This part includes author and subject indexes as well as a guide to the more significant literature. Second, the technical principles which must be adhered to in order to do a technically sound AE test on a composite sample are described in some detail. This part includes all aspects of standard testing and data analysis. Third, a representative survey of typical proven applications of AE to composites is presented. This survey has two basic divisions: (1) the application of AE to material studies of composites; and (2) the application of AE to quality control and/or nondestructive evaluation. Finally, a review of the progress in the research areas of AE and composites is given. This review covers the specific areas which have not yet been brought to maturity. In appropriate cases critical comments are made as well as suggestions for future work.

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PREFACE

This project was accomplished as part of the U.S. Army Aviation Research and Development Command Manufacturing Technology program. The primary objective of this program is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in production of Army material. Comments are solicited on the potential utilization of the information contained herein as applied to present and/or future production programs. Such comments should be sent to: U.S. Army Aviation Research and Development Command, ATTN: DRDAV-EGX, 4300 Goodfellow Blvd., St. Louis, MO 63120.

The work described in this report was accomplished under a contract monitored by the Army Materials and Mechanics Research Center. Technical monitor for this contract was Dr. R. J. Shuford.

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Acknowledgement

This work was also performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-ENG-48 during the author's research leave at the University of Denver.

Contents

Part 1: A Bibliography and Guide to Acoustic Emission from Composites

Introduction

The purpose of this part of the report is to describe the conditions under which the bibliography in this section was put together and to provide a guide to the bibliography so as to make it easier for the user to find the significant references in the area of his interest.

A total of 314 references are listed in the bibliography. The following guidelines were used to establish which references were to be listed and how they were to be listed. First, only references which dealt both with composites (see Part 2 for a definition) and acoustic emission (AE) were listed. Thus references which may be of interest but dealt only with AE or only with composites were not included. Second, only references which we were able to obtain a copy of were listed. Thus limited distribution or internal reports were not listed. Third, only references which were available to anyone were listed. Thus, for example, proprietary references which we had copies of were not listed. Fourth, we did not list references which dealt with only the following composites and AE: bi-metallics, concrete, honey-comb with metal skins, and wood. Fifth, we did not list references which dealt only with the stress-wave factor and composites. This field seems to the author to belong to the application of ultrasonics to composites. Sixth, references (with English texts) which had less than 20% or less than 3 pages of text devoted to AE and composites were considered to be minor references. The minor references are unmarked while the rest of the English references are listed with one or two asterisks. Seventh, all references were available to us in English except as indicated. (Note: Non-English papers were not reviewed for

Parts 3 & 4). Eighth, the references are listed in alphabetical order based on the first listed author's last name and beginning with the earliest publication with that author listed first. Ninth, papers without an author are listed at the end of the bibliography. Tenth, in cases where the same report (in our opinion) appeared as two or more separate publications we listed the reference by its most accessible reference and included the other publication in that listing. Eleventh, references designated with two asterisks are considered to be major reports with more than 90% of their contents devoted to AE and composites; one asterisk denotes between 20% and 90% of their contents devoted to AE and composites. Twelfth, we also included references which consisted only of an abstract of an oral presentation. These references were always listed as a minor reference. Thirteenth, papers which dealt with AE and matrix materials without their composites were also excluded from the reference list. Fourteenth, each paper's bibliography was searched for additional references which were then listed as well.

General Information

Of the total of 314 references, 82 were listed as minor references and 158 were major references which had 90% or more of the reference devoted to AE and composites. Figure 1 shows the distribution by year of publication of all references. It is noteworthy that the first reference appeared in 1961, and before 1970 only a total of seven references had appeared and only two of these appeared in technical journals. Thus the technology of AE and composites is ·y much a technology which only began in the 1970's. It is also of interest that the rate of publication in the field has been approximately steady at

an average of about 26-32 papers per year since 1973. There may be a slight peak in 1979-80, but that may be because we have not yet found all the papers published in 1981 and 1982. The total volume of printed material in this field is represented by a stack of papers 8-1/2 x 11 inches by approximately 36 inches high.

A study of the locations from which references originated also provides some interesting results. Establishing a criteria of at least 3 publications in the years 1978-82 or a total of 5 or more major publications, we find that over 33% of the papers originated at 21 locations. These locations along with the authors which have been or still are associated with publications from these locations are listed below. The key individuals' names are underlined.

1. Aerojet General and/or Acoustic Emission Technology Corporation, Sacramento, Ca., USA - <u>A.T. Green;</u> C.S. Lockman; H.K. Haines; R.K. Steele; C.F. Morais; R.J. Landy.

2. Army Materials and Mechanics Research Center, Watertown, Mass., USA - <u>Y.L. Hinton;</u> <u>R.J. Shuford;</u> W.W. Houghton.

3. Battelle Institut eV; Frankfurt am Main, Germany - <u>J. Becht;</u> <u>J. Eisenblatter;</u> <u>H.J. Schwalbe;</u> H. Ahlborn; P. Jax; G. Faninger.

4. Dunegan/Endevco, San Juan Capistrano, Ca., USA - <u>J.R. Wadin;</u> <u>A.A. Pollock;</u> H.L. Dunegan; J.R. Mitchell; A.T. Green; A.S. Tetelman; D.O. Harris; F.A.I. Darwish; M.P. Kelly; W.J. Cook.

5. Ecole Nationale Superieure des Mines de Paris, Evry Cedex, France - A.R. Bunsell; D. Laroche; J.C. Lenain.

6. IIT Research Institute, Chicago, Ill., USA - S.W. Schramm; I.M. Daniel; W.G. Hamilton; T. Liber.

7. Imperial College, London, England - H.C. Kim; W.G.B. Britton; R.W.B. Stephens; A.P. Ripper Neto.

8. Israel Institute of Technology, Haifa, Israel - A. Rotem; J. Baruch; E. Altus; S.R. Bodner.

9. Lawrence Livermore National Laboratory, Livermore, Ca., USA - M.A. Hamstad; T.T. Chiao; D.M. Boyd; E.S. Jessop; M.A. Marcon; J.E. Hanafee; R.G. Patterson; R.G. Liptai; D.O. Harris; R.B. Engle; C.A. Tatro.

10. Lockheed-Georgia Company, Marietta, Georgia, USA - C.D. Bailey; J.M. Hamilton, Jr.; W.M. Pless; S.M. Freeman.

11. Massachusetts Institute of Technology, Cambridge, Mass. - USA - J.H. Williams, Jr.; D.M. Egan; F.J. McGarry; E.H. Rowe; C.K. Riew; S.S. Lee.

12. Monsanto Corporation, St Louis, Mo., USA - T.J. Fowler; R.S. Scarpellini; P.J. Conlisk; E. Gray.

13. National Physical Laboratory, Teddington, Middlesex; England - B.J. Keene; G.D. Sims; D.G. Gladman; G.D. Dean; B.E. Read; B.C. Western.

14. Rocket Propulsion Establishment, Westcott, Aylesbury, Bucks, England - L.A. Kerridge; D.S. Dean.

15. Rockwell International, Science Center, Thousand Oaks, Ca., USA - L.J. Graham; R.K. Elsley.

16. Royal Aircraft Establishment Farnborough, Hants, England - P.F. Dingwall; D.E.W. Stone; D.L. Mead.

17. Technische Universitat Hannover, Hannover, Germany - K.P. Buhmann; H.A. Stelling; Th. Winkler.

18. University of Bath, Bath, England - B. Harris; M.G. Phillips; F.J. Guild; R.D. Adams; A.O. Ankara; C.R. Brown; F.J. Ackerman.

19. Universite de Technologie de Compiegne, Compiegne, France - F.X. De Charentenay; M. Benzeggagh; P. Bae; A. Chaari; P. Gaillard; J.F. Chretien; M. Bethmont; K. Kamimura; A. Lemascon.

20. University of Sussex, Falmer, Brighton, Sussex, England - A.R. Bunsell; M. Fuwa; B. Harris; M. Arrington; R. Rothwell.

21. Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA - E.G. Henneke II; K.L. Reifsnider; J.C. Duke, Jr.;

A.K. Govada; A. Lemascon; C.T. Herakovich; G.L. Jones; M.P. Renieri; H.W. Herring; S.S. Russell; R.C. Stiffler; W.W. Stinchcomb; L.A. Marcus; R.S. Williams; G.H. Wilson III.

Locating References of Interest

A subject index is provided for the listing of references. An author index listing 316 names is also provided. Also for the last 5 years (1978-82) a listing of major references by year is provided. For selected topics in the subject index, references, which in this author's opinion are good typical background material, are underlined. A separate listing (by year) of survey or review references in the field of AE and composites is also given.

Acknowledgement

The use of T.F. Drouillard's (Rockwell International, Rocky Flats Plant, Golden, Co., USA) files of papers is gratefully acknowledged. The help of R.F. Fisher and M. Guhathakurta in reading and organizing the literature survey is also gratefully acknowledged.

Figure Captions

Figure 1.1 Rate of publications on AE and Composites.

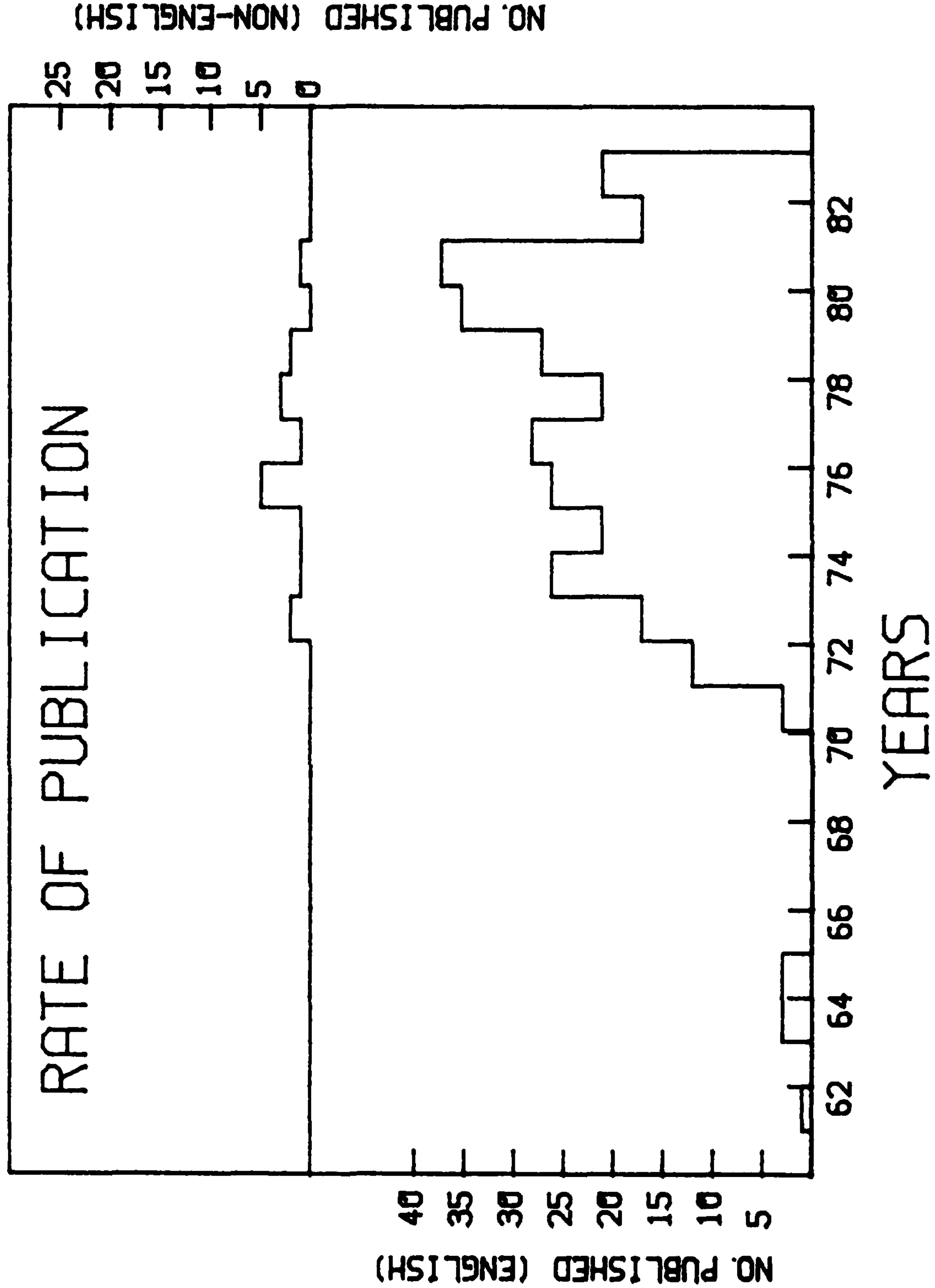
RATE OF PUBLICATION
NO. PUBLISHED (NON-ENGLISH)
25 20 15 10 5 0
NO. PUBLISHED (ENGLISH)
40 35 30 25 20 15 10 5
62 64 66 68 70 72 74 76 78 80 82
YEARS

Fig. 1.1

Appendix I: List of References

References are rated in the left-hand margin according to the amount of their content devoted to acoustic emission and composites. References designated with two asterisks (**) are considered to be major works with more than 90% of their contents devoted to acoustic emission/composites; one asterisk (*) denotes between 20% and 90% of the contents devoted to acoustic emission/composites; unmarked references are considered minor, with less than 20%, or less than 3 pages devoted to acoustic emission/composites; references designated (a) are not rated because they were published in a foreign language with no English translation available.

** 1. C. H. Adams. "On the SPI/CARP Recommended Practice for Acoustic Emission Testing of Fiberglass Tanks and Vessels." *Journal of Acoustic Emission,* JACED, 1(3):165-172. July 1982.

** 2. C. H. Adams. "Recommended Practice for Acoustic Emission Testing of Fiberglass Reinforced Plastic Tanks/Vessels." Session 27-A, pp 1-13 in *Preprint of the 37th Annual Conference, Reinforced Plastics/Composites Institute: Leading from Strength.* Society of the Plastics Industry, Inc., New York. 1982. conference held in Washington, D.C. Jan 11-15, 1982.

3. R. D. Adams and J. E. Flitcroft. "Assessment of Matrix and Interface Damage in High Performance Fibre Reinforced Composites/ L'evaluation des dommages de la matrice et des interfaces dans les composites renforcees aux fibres a haute resistance a la rupture." Bristol University, Bristol, England; Paper 4B/3 in *Proceedings of the Eighth World Conference on Nondestructive Testing.* volume containing Sections 3F, 3B, 4B. International Committee for Nondestructive Testing, Secretariat du Cofrend, Institut de Soudure, 32 Boulevard de la Chapelle, 75880 Paris Cedex 18, France. 1976. conference held in Cannes, France. Sep 6-10, 1976. (paper in English).

** 4. H. Ahlborn, J. Becht, and J. Eisenblatter. "Anwendung der Schallemissionsanalyse bei Untersuchungen uber die Risszahigkeit von Faserverbundwerkstoffen (Application of Acoustic Emission Analysis for Studying Fracture Toughness of Composites)." Battelle-Institut eV, Frankfurt am Main, Germany. 1973. (in German); paper presented at the Seminar on Schadigungsgrenzen bei GFK (Damage Limits in GFK), Karlsruhe, Germany. Mar 1973; UCRL-Trans-10785. translated for Lawrence Livermore Laboratory, Livermore, California. Nov 1974. [NTIS].

5. H. Ahlborn, J. Becht, and H. J. Schwalbe. "Untersuchungen zur 'Risszahigkeit' verschiedener GFK-Laminate unter Einsatz der Schallemissionsanalyse (SEA) (Investigations on 'Fracture Toughness' of Various GRP Laminates Using Acoustic Emission Analysis)." *Kunststoff-Berater,* KUBEA, 20(6):300-306. 1976. (in German).

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7. L. J. Anderson and T. G. Hagemeier. "Fiber Reinforced Plastic Vessel Testing Using Acoustic Emission." pp 36-37 in *Paper Summaries: National Fall Conference, American Society for Nondestructive Testing, October 15-18, 1979, St. Louis [Missouri].* American Society for Nondestructive Testing, Columbus, Ohio. 1979.

8. R. T. Anderson and T. J. DeLacy. "Nondestructive Testing of Advanced Composites." *Metal Progress,* MEPOA, 102(2):88-92. Aug 1972.

* 9. M. P. Ansell and B. Harris. "The Relationship Between Toughness and Fracture Surface Topography in Wood and Composites." pp 309-318 in *Mechanical Behaviour of Metals.* Edited by K. J. Miller and R. F. Smith. Volume 3. Pergamon Press, Oxford, England and Elmsford, New York. 1980. proceedings of the Third International Conference on Mechanical Behaviour of Materials (ICM-3), held in Cambridge, England. Aug 20-24, 1979. [ISBN 0-08-024739-3 (3-volume set)].

** 10. M. Arrington. "Acoustic Emission from Real and Model Composites." pp 3-1 to 3-5 in "Newletter on the Non-Destructive Testing of Composite Materials and Adhesive Bonded Joints." Issue Number 2. Royal Aircraft Establishment, Farnborough, Hants, England. July 1973.

* 11. M. Arrington. "Some Aspects of Interfacial Bonding in Composites with Special Reference to Carbon and Glass Fibre Reinforced Plastics." Ph.D. Thesis. University of Sussex, Falmer, Brighton, Sussex, England. Sep 1976.

12. M. Arrington and B. Harris. "Some Properties of Mixed Fibre CFRP." *Composites,* CPSOA, 9:149-152. July 1978.

13. M. G. Bader, J. E. Bailey, P. T. Curtis, and A. Parvizi. "The Mechanisms of Initiation and Development of Damage in Multi-Axial Fibre-Reinforced Plastics Laminates." pp 227-239 in *Mechanical Behaviour of Metals.* Edited by K. J. Miller and R. F. Smith. Volume 3. Pergamon Press, Oxford, England and Elmsford, New York. 1980. proceedings of the Third International Conference on Mechanical Behaviour of Materials (ICM-3), held in Cambridge, England. Aug 20-24, 1979. [ISBN 0-08-024739-3 (3-volume set)].

** 14. P. Bae, A. Chaari, P. Gaillard, and J. F. Chretien. "Pattern Recognition Technique for Characterization and Classification of Acoustic Emission Signal." pp 134-136 in *Proceedings - 5th International Conference on Pattern Recognition.* Volume 1. Institute of Electrical and Electronics Engineers, Inc., New York. 1980. conference held in Miami Beach, Florida. Dec 1-4, 1980. [IEEE Catalog No. 80CH1499-3 (2-volume set)].

** 15. C. D. Bailey, S. M. Freeman, and J. M. Hamilton. "Detection and Evaluation of Impact Damage in Graphite/Epoxy Composites." pp 491-503 in *Materials & Processes - In Service Performance.* National SAMPE Technical Conference Series, Volume 9. Society for the Advancement of Material and Process Engineering, Azusa, California. 1977. conference held in Atlanta, Georgia. Oct 4-6, 1977.

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** 20. R. Bardenheier. "Schallemissionsuntersuchungen an polymerer Verbundwerkstoffen. Teil II: Experimentelle Ergebnisse (Acoustic Emission Monitoring of Polymeric Composite Materials. Part II: Experimental Results)." *Zeitschrift fur Werkstofftechnik/Journal of Materials Technology,* ZWKTA, 11:101-110. Mar 1980. (in German); NASA TM-76523. translated for National Aeronautics and Space Administration, Wasthington, D.C. Feb 1981. [NTIS: N81-20187]; UCRL-Trans-11628. translated for Lawrence Livermore Laboratory, Livermore, California. Sep 1980. [see Reference 19 for Part I].

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** 30. C. R. Brown. "Acoustic Emission from GRP." pp 7-1 to 7-5 in "Newsletter on the Non-Destructive Testing of Composite Materials and Adhesive Bonded Joints." Issue Number 4. Royal Aircraft Establishment, Farnborough, Hants, England. July 1975.

** 31. T. S. Brown and J. R. Mitchell. "Acoustic Emission Evaluation of Automotive Hybrid Composites and Attachments." Section 26-B, pp 1-6 in *Preprint of the 35th Annual Conference, Reinforced Plastics/Composites Institute: Rising to the Challenge*. Society of the Plastics Industry, Inc., New York. 1980. conference held in New Orleans, Louisiana. Feb 5-8, 1980.

* 32. K. P. Buhmann. "Zum Bestimmen der Schadigungsgrenze von GFK-laminaten - Neue Zerstorungsfreie Methoden und Ihre Eignung als Fertigungskontrollverfahren (The Determination of the Damage Limit of GFK Laminae - New Nondestructive Methods and Their Suitability as Production Control Processes)." *Kunststoffe,* KUNSA, 62(12):875-880. 1972. (in German); "The Determination of the Damage Limit of GFK Laminae - Destruction-Free Methods and Their Suitability as Production Control Processes." translated for Lawrence Livermore Laboratory, Livermore, California. [copy available from Dr. M. A. Hamstad, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94550, U.S.A.].

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Appendix II: Author Index

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Appendix III: Subject Index

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Appendix IV: Listing of Major References with Greater than 90% on AE and Composites by Year for the Period of 1978-1982

1978: [29, 72, 109, 110, 148, 151, 157, 165, 194, 209, 247, 248, 257, 285, 286, 296, 299, 301, 311, 312]

1979: [52, 63, 73, 82, 83, 84, 111, 112, 113, 114, 125, 138, 150, 158, 166, 170, 211, 219, 249, 253, 269, 300, 302, 303]

1980: [9, 14, 17, 20, 31, 51, 58, 59, 60, 67, 68, 70, 86, 87, 115, 116, 133, 152, 169, 195, 220, 229, 264, 265, 278, 308]

1981: [102, 153, 155, 167, 172, 173, 212, 230, 262, 298]

1982: [1, 2, 53, 61, 88, 100, 156, 178, 201, 222, 231, 233, 258, 282, 290, 304]

Appendix V: Survey and Review References

Surveys and Reviews on AE and Composites

1974: Hamstad [144].

1975: Carlyle [41].

1976: Guild *et al*. [132].

1978: Williams and Lee [301], Hamstad [151], Crivelli Visconti and Teti [50].

1979: Green and Landy [129], Hamstad [150], Mitchell [211].

1980: Duke and Henneke [70], Bardenheier [20], Williams [308].

1981: Mitchell [212], Reynolds [239].

1982: Scott and Scala [258], Hamstad [156].

Part 2 - Basic Principles of Acoustic Emission for Application to Composite Materials

Introduction

The intent of this section is to set out the technical principles which must be adhered to in order to do a technically sound AE test on a composite sample. It is relatively simple to attach an AE sensor to a composite and then load the sample. It is a much more complicated process to carry out an AE test which conforms to the known physics relating to AE testing. For completeness, this section will be self-contained in that it will not be assumed that the reader understands AE testing of metal samples or structures. This section will also assume that the reader is planning on doing "production testing" of composites with AE monitoring ("production testing" in the sense that at least several identical samples will be tested). The organization of this section will be to first treat each of the physical entities involved in an AE composite test; then aspects such as AE data and its analysis will be treated.

The Basic Source of AE

An AE event is a complicated stress wave which is generated at a location in a structure by a rapid change in the local stress state. This can be expressed by the following

$$\Delta\sigma_{ij}\,(\underset{\sim}{x},\ \Delta t,\ \Delta V) \qquad (2.1)$$

Where $\Delta\sigma_{ij}$ is the change in each of the independent stress components necessary to describe the stress state at that point in the structure, $\underset{\sim}{x}$ is a vector describing the location at which the rapid change in

stress state occurs, Δt is the time interval over which the stress change occurs, and ΔV is the volume (or area for certain AE sources) of the structure which experiences the stress change. A typical example might be a microscopic failure of a fiber in a composite structure. In this case the stored energy which is rapidly released supplies (among other things) the energy contained in the resulting stress wave or AE.

In reality the model we have adopted is simplified in that the AE event is actually generated by the change in σ_{ij} as a function of both time and spacial coordinates in the region defined by ΔV. But since this more complicated model adds nothing to our development here, we will use the simplified model.

The factors expressed in equation (2.1) can provide some insight into the intensity of the AE event which is generated. For example, the AE event will be more intense for larger $\Delta\sigma_{ij}$'s, for shorter Δt's, and for larger ΔV's. Conversely, the AE event will be less intense for smaller $\Delta\sigma_{ij}$'s, for longer Δt's, and for smaller ΔV's.

Certain dynamic processes can also generate AE events; for example, sliding friction between two surfaces moving relative to each other. By including "surface" tractions in the $\Delta\sigma_{ij}$ of equation (2.1), these dynamic processes can also be included in the general simplified formulation.

Before moving to the next sub-section, it is important to emphasize that the AE event at the level at which we can currently measure it (or observe it) is a complex propagating stress wave which will follow the physical laws which govern stress waves. Hence, the wave propagation will be intractable for all but the most simple structures

(for example isotropic-infinite mediums). It will be important to keep these ideas in mind as we discuss AE testing of practical composites which are normally of complex and finite geometry, as well as anisotropic.

Composite Test Specimens or Structures

Due to the complexity of stress wave propagation in composites as well as other factors (such as the currently unknown AE source events and the usual commercial AE sensors that respond to surface displacements and velocities in a complex frequency dependent fashion), it is not possible at present to make measurements of a real AE event and then calculate the source function (say that represented by equation 2.1). Hence, AE as a nondestructive evaluation technique (NDE) for composites is, at this time, primarily a comparison technique. This fact means that, to be useful, baseline AE data must be gathered from a series of "identical" samples. Then techniques can be established to identify various deviations from the "identical" samples. It is necessary to establish what is meant by the term "identical samples."

The following factors must be controlled for samples to be identical. First, the relevant stress wave propagation characteristics must be the same. This requirement means that the sample geometry must be the same, the sample material (mechanical properties, e.g., modulus and density) must be the same, and the stress wave observation points and techniques must be the same (i.e., sensors and sensor locations). Second, the stress field throughout the sample must be the same. This fact inherently implies that the sample is loaded or stressed in the same way and that the general flaw structure in the sample shall be the same (i.e., same sizes and locations or same sizes and uniformly dis-

tributed throughout the structure). Thirdly, the local microscopic AE sources (e.g., microscopic failure mechanisms) must be the same. This requirement means that typical microscopic strengths and deformation properties must be the same. Now since composites can only be reliably described by statistically based analysis procedures, the sameness that is required here is statistical in nature. This concept will be discussed in more detail later in this part. It should be noted that we have taken a relatively restricted point of view about the definition of the identical samples needed for comparison. There are currently AE applications for which this level of identicalness has not been necessary, but in our opinion it is best to start with the above approach and then prove, if possible, that a less restrictive definition of identicalness is sufficient.

In addition to its application for NDE, AE can be used for basic studies of composite materials or structure studies. For these studies, there are some additional comments which need to be made with respect to test specimens and relevant requirements. For these types of studies, the first requirement is to test a sufficient number of identical samples so that the AE that occurs for each sample can be characterized relative to the AE that randomly occurs from different samples. The characteristic AE patterns can then be correlated with deformation and micro-failure mechanisms which are known to occur at various loads from other inputs (e.g., mathematical analysis, microstructural studies, microfailure observations, etc.).

Test Installation or Test Fixturing

Since the composite test specimen must be supported in some way and is normally externally loaded, the test fixturing becomes a key part of the test system. Normally, the task of assuring that the load is applied in the same way is not difficult. A more subtle but probably just as important a factor concerns the interaction of the test fixture and the test specimen from the point of view of wave propagation characteristics. The stress waves generated by an AE event will propagate throughout the test specimen as well as the test support and loading fixturing. The two major variables which are of importance here are, first, that the fixturing be identical from a wave propagation point of view (in all aspects including, for example, attenuation) and, second, that the interfaces between the composite specimens and the fixturing have identical wave propagation characteristics. The reason for these requirements is that the time varying amount of energy which reaches the AE sensor from a given AE event will depend on how much of the original energy goes to and is dissipated in other parts of the test fixture on composite test structure. A significant variable in this partition of energy from test to test can be the condition of interfaces, particularly between the specimen and the test fixture, and to a lesser degree between the various parts of the test fixture. For example, an interface between the test specimen and the test fixture which is coupled by oil or water will result in significantly more of the energy (from a given AE event) going into the fixture rather than reaching the AE sensor. Thus comparing tests with dry vs. "wet" interfaces may be very difficult. Another typical example which might be

encountered is in proof testing of composite pressure vessels. Here a metal liner will result in considerably different coupling (with respect to AE wave propagation) of the AE energy into the hydraulic fluid than when a rubber liner is used. Similarly, during proof testing of composite tanks by filling them with fluid, the potential wave propagation paths change depending on the fluid level. Hence, AE energy from a particular AE event reaching an AE sensor will vary depending on the fluid level.

Since there are significant signal propagation losses in composites, the relative significance of fixture changes will depend on the size or volume of the composite article under test. In general, effects will be much more significant for small articles, but even in a large composite structure effects of changes in the near vicinity of AE source locations could be significant. Again, we have taken a view that may be more restrictive, but it seems to be best to start with the more restrictive approach and relax if it is not required.

The use of artificial AE sources (e.g., Pentel pencil lead breaks) can be used to determine the potential significance of unavoidable fixture changes. But some care should be exercised since the source events (eq. 2.1) in a composite may be considerably different than that for the lead break. Potentially different types of artificial sources may need to be developed to correspond to the different sources in composites. It should be noted that that the lead break could also be used to check effects of some changes in specimens. But again, similar precautions must be applied, since at this point we do not know how closely the lead-break source event corresponds to the different real AE events which can occur in composites.

Even identical test and support fixturing may not result in the same wave propagation characteristics each time a new test specimen is mounted in the fixturing. Lack of cleanliness or changes in the test specimen installation procedure can result in significantly different wave propagation characteristics of the specimen/fixture assembly. Again, this aspect can be checked for significance by use of a Pentel pencil lead break (this technique will be discussed in further detail in the calibration section).

Couplants and Waveguides

The stress wave energy from an AE event is usually transferred from the test specimen to the commercial AE sensor by means of a couplant. The couplant, which is normally viscous, provides for more efficient coupling than dry coupling (i.e., the face of the AE sensor in contact with the test structure). There are several desired properties which guide the selection of the couplant material. First, it must provide good acoustic coupling over the desired frequency range. Second, the couplant should be compatible (from a chemical point of view) with both the composite and the AE sensor. Third, the couplant material should be easy to remove from both the composite and the AE sensor without damaging either. Fourth, the couplant should have a consistent viscosity from batch to batch, or if the couplant is an adhesive it should have consistent moduli. Fifth, the couplant or adhesive should maintain a consistent viscosity or modulus over the time period it is used and at the temperatures used.

In the past, too little attention has been paid to the application of couplant to AE transducers. There has been little or no control of the amount of couplant or of the volume of voids in the

couplant. The philosophy has often been to use a lot of couplant in a rather sloppy fashion. Unfortunately, this is the only way to do it when it is not feasible (for economic or time reasons) to use special fixturing such that a small, precise amount of couplant can be effectively used (more on this in the sections on sensors and calibration). With the advent of the lead-breaking technique for calibration purposes, it has been found that there are several improvements that can make the coupling more uniform for repeated application to test parts. These concepts have come as a result of capturing the AE event output with a transient recorder for lead breaks made with a precise mechanical lead breaker. By varying different parameters, the following practices or techniques have been found to lead to the most repeatable coupling practices. First, use a small diameter sensor. Second, use a large hypodermic needle to apply a uniform volume of couplant to the center of the transducer face. Third, do not hand spread the couplant, but allow it to be spread when the transducer is brought against the test specimen by a fixed coupling force. Fourth, do not "wring" the sensor in or apply any force in the direction which will tend to pull the sensor away from the test specimen. Development of these techniques requires that the technicians undergo training and practice with the use of a mechanical lead breaker and a transient recorder (to evaluate the development of their technique). The amount of couplant used should not be such that it overflows at the edge of the sensor face. The reason for this is that since the couplant is viscous, excess couplant or couplant spilled on the test sample will absorb AE energy and thereby potentially reduce the sensitivity of the AE equipment.

For composites made with certain fabrication techniques (e.g., filament winding), the composite surface may not be as smooth as is normally the case with other materials. In such cases, in order to have relatively uniform coupling from part to part, the best amount of couplant to use may have to be determined experimentally by applying various amounts to several parts and determining which amount gives the most uniform time domains for mechanical lead breaks.

AE Sensors - Type, Location, Attachment

Commercial AE sensors have a piezoelectric crystal which gives a voltage output related to its deformation. At this point in the development of AE monitoring of composites, there do not seem to be overwhelming technical reasons that dictate the selection of one AE sensor type over another design. In spite of the fact that sensor manufacturers advertise sensor resonances of tens to hundreds of kilohertz, we have found that these same sensors perform quite well down to a few kilohertz. Hence, one philosophy has been to purchase the least expensive sensors and to machine the epoxy face down such that the contact area is reduced to about 1/4 inch in diameter (to improve coupling consistency). The low cost sensor is chosen since when samples are taken to failure, the sensor can be damaged due to the energy released at macroscopic failure.

There are basically two classes of AE sensors which are commercially available, resonant and non-resonant. The resonant sensor will normally have more sensitivity, but often the signals from composites are of high amplitude, so sensitivity is not a problem. Further, at the lower frequency bandpasses, which seem to be most useful for composites (see discussion later in this section), the signal ampli-

tudes are even larger. The non-resonant sensor has a flatter frequency response curve than the resonant sensors, but, to date, this characteristic has not been exploited in routine testing.

In general, commercial AE sensors respond to deformation (stress) waves in a complex fashion which involves both normal and inplane deformations and velocities in the test samples. For this reason, it is currently impossible to calibrate such sensors in an absolute sense with respect to the way they actually operate in practice. Thus, we have adopted a different approach which will be covered in a later section in this part. In Part 4 there will be some discussion of new sensor concepts which will lend themselves more easily to normal calibration concepts. Since commercial sensors currently cannot be absolutely calibrated, even sensors of the same design should be treated as unique until it has been proven otherwise. This means keeping track of sensor serial numbers.

To return to choice of sensors, a few more comments can be made. For large composite structures, there may be significant manpower economies in using sensors which have an integral pre-amplifier. On the other hand, such sensor-preamplifier combinations preclude the technique of connecting more than one sensor to the same preamplifier. This latter technique will result in significantly less electronic equipment costs to effectively "cover" a large composite tank, but it will result in higher manpower costs. In general, use of two sensors into the same preamplifier will result in a loss of about 6 dB in signal amplitude for a given event.

There are several factors which enter into the decision concerning sensor locations. The key information which is required is the

AE signal propagation loss which occurs with distance in the composite structure as a function of the electronic bandpass. This information can be gathered by using pencil-lead breaks right next to the AE sensor (unless it is possible to always locate sensors some distance from all AE sources) and at various distances and directions from the sensor. Since composites are in general anisotropic and of varying thickness, the signal propagation losses may vary in different parts of the composite. Hence, the relevant propagation data needs to be generated throughout the structure. Normally, the lowest electronic bandpass is chosen which is consistent with the frequencies of any extraneous noise sources which are present in the test environment and cannot be eliminated for cost or other reasons (for more on this, see a later section in this part). Once the propagation characteristics of the selected bandpass have been determined, then it is necessary to decide how much signal propagation loss is acceptable. Since peak amplitude is one characteristic that has been used to judge the severity of the damage mechanism which caused an AE event in a composite, it may be necessary to limit potential amplitude propagation losses to no more than 6-12 dB. The acceptable propagation loss along with the relevant experimental propagation losses will determine the spacings of the AE sensors in order to effectively cover the composite article which is to be monitored with AE. For large composite structures, the number of sensors required may be over 100. In many cases, the number of sensors required can be cut significantly due to prior knowledge of likely failure regions based on stress analysis and/or test experience. In such cases, it is only necessary to monitor the regions where failure can occur.

It is important to note that propagation losses of AE event energy are not as severe as those with AE peak amplitude (see later section on propagation). Hence, if energy measurements are used instead of peak amplitude, sensor spacings can be greater and still effectively cover the whole part.

The attachment technique for AE sensors (i.e., the means by which the AE sensor is held in contact with the composite article) needs a good deal of attention for a number of reasons. Ideally, the best technique is to hold the sensor by means of some external fixturing which does not come in contact with the composite. The reason for this is that any attachment fixturing which comes into contact with the composite can change the AE wave propagation characteristics and provide a path for AE energy away from the sensors. This could reduce the sensitivity at best, and at worst could cause extraneous AE to be generated due to the strains in the composite during testing (strains for the design stresses in composites are often 3 or 4 times those in metal structures). Also, unless special care is taken in the design and installation of the attachment fixturing, it may not couple the sensor the same way each time, or it may result in changes for each installation in the amount of AE event energy which is transferred away from the specimen into the attachment fixturing. In either of these cases, there are problems due to inconsistencies from sensor to sensor and from test to test.

In actual practice, it is not always easy or cost effective to attach sensors in the ideal manner. When compromises must be made, the effect of these compromises should be evaluated by the use of mechanical lead breaks while capturing the analog AE events on a transient

recorder with oscilloscope. Based on the changes in AE event amplitude, event duration, and time distribution of AE energy, the significance of attachment compromises can be evaluated. The basic design principles for attachment of AE sensors are: 1) the attachment device should hold the sensor in contact with the specimen such that the sensor face is parallel to the tangent plane of the composite at that point; 2) the sensor should be held against the composite with sufficient force such that gravity does not cause the sensor "contact" force to be much larger or smaller in certain places on the composite (i.e., the sensor contact force should be uniform for all locations); 3) each sensor should be placed at the same position on each successive composite part; 4) the sensor contact force should be sufficient to spread the couplant without "wringing in" the sensor; 5) the attachment fixturing should allow easy replacement of the couplant (i.e., removal of the sensor and cleaning the sensor face and composite and reapplying the couplant); 6) the attachment fixturing should create no significant extraneous AE during the test and should not constrain normal deformation of the composite; 7) the attachment device should perturb the AE wave propagation as little as possible and the perturbation which does occur should be the same for each sensor installation; and 8) the attachment fixturing should be simple and quick to install.

Cables: Sensor to Pre-Amplifier and Others

The cable that connects the preamplifier to the AE sensor is normally a coaxial cable. There are three aspects of its application with which to be concerned. First, since the cable is not perfectly shielded, it can act as an antenna with respect to electro-magnetic radiation. Thus, to keep this electronic noise low (to improve the

signal to noise ratio), the length of this cable should be kept relatively short (e.g., a few feet) unless electro-magnetic radiation can be eliminated. Second, the AE sensor is a receiver and looks electrically as if it is a capacitor. The electrical charge from the sensor element is divided between the "capacitance" of the sensor and the combined capacitance of the cable and preamplifier. Since the capacitance of the cable varies with length, the result is that the sensitivity of the AE sensor can vary considerably with changes in the length of this cable. To overcome this potential difficulty, the practice often is to use a standard cable length for all preamplifier cables. Third, the characteristic impedance of this cable is also an important factor because the cable should be terminated with its own characteristic impedance for maximum power transfer. Typically, the AE preamplifier and secondary amplifier have 50 Ω output and input impedances respectively. Thus, normally 50 Ω cable is used for all cable attachments in the AE system. In some cases where the AE secondary amplifier does not have a 50 Ω input impedance, it is necessary to externally terminate the system with a 50 Ω terminator.

For other cables in the AE system, the primary consideration is cable length. For example, the length of cable between the preamplifer and the main AE electronic unit can vary from a few feet to 1,000 ft or more. Unless a line-driver is used, the losses in a long cable can be considerable.

Special cables are normally used only between the preamplifier and the main AE electronics unit. The reason for this is that the commercial AE equipment manufacturers have chosen different ways to power their preamplifiers. Some use regular coaxial cables while

others use a four-conductor cable. When using AE components from different manufacturers, care must be exercised in the choice of cables for the preamplifier to main unit connection.

In practice, the primary difficulty with cables is the introduction of ground loops due to broken connections which occur during use. Ground loops cause the electronic noise level to increase and thereby reduce the signal to noise ratio.

<u>Preamplifiers</u>

Preamplifiers provide gain to the analog AE signals. Their primary function is to increase the signal level of the AE signals so that they are considerably above the level of the electronic noise that is induced by the antenna effect of the total length of cable between the AE sensor and the main electronic unit. Normal commercial AE preamplifiers come in either 40 dB or 60 dB gain models (Note: $\Delta dB = 20 \log_{10} \frac{Vout}{Vin}$, where ΔdB is the gain in decibels, V_{in} is the input voltage and V_{out} is the output voltage). In most cases, commercial AE preamplifiers are powered by DC voltage coming from the main AE electronic unit. Preamplifiers can also be purchased as battery powered units. The battery powered preamplifiers reduce extraneous electronic noise since they are independent of normal commercial power which can be quite "dirty."

There are four main specifications for the performance of preamplifiers. First is the gain. Since composities often have relatively high amplitudes of AE signals compared to metals, often 20 dB or 40 dB are sufficient (preamplifiers with 0 dB gain have been used in some cases). The best solution to the need for variable preamplifier gain is probably to purchase preamplifiers with a switch that will allow a

choice of either 20 or 40 dB. The need for variable preamplifier gain leads to the second main specification, namely, the maximum output voltage of the preamplifier. A typical figure might be 10 volts peak-to-peak. When the input voltage is large enough so that if the fixed gain of the preamplifier is applied, an output voltage of greater than 10 volts p.p. (1 volt p.p. in some cases) would occur, then the preamplifier is said to be saturated (or the signal is clipped). This condition results in a distorted wave form and a loss of the real signal level. Since it is often difficult to determine if saturation will occur, it is normally best to be on the safe side, which means using lower preamplifier gain. The third main concern with the preamplifier is its electronic bandpass. Typically, commercial AE preamplifiers come with "plug-in" filters, that is, the bandpass can be changed with a simple replacement of a module inside the preamplifier. The filter bandpass is normally specified by the 3 dB down points. For composites, the choice of a lower bandpass, say 5-10 kHz, will normally result in less signal propagation losses than a higher bandpass, say 100-300 kHz. There are two reasons for this result: i) low frequencies do not attenuate as rapidly with distance as do high frequencies; and ii) to reduce signal propagation losses the high frequencies must be filtered out electronically for AE events which originate near the AE sensor. It should also be mentioned that the electronic noise out of the preamplifier depends on the bandpass. The wider the bandpass, the greater the electronic noise. Hence, when comparing electronic noise specifications of different preamplifiers, the bandpass must be the same.

The fourth concern with the preamplifier is its dynamic range. The dynamic range is the range in signal level between the background electronic noise level and the maximum output voltage of the preamplifier. Since the noise level of the preamplifier is normally quoted in root-mean-square (rms) voltage, the dynamic range is not always readily apparent. The electronic noise has random amplitudes, and hence the peak noise amplitudes can be on the order of 12-18 dB above the rms noise level. Since the AE events in composites have a very wide dynamic range, it is useful to have a preamplifier with a dynamic range considerably greater than 60 dB as a minimum. Ideally, 80-100 dB of dynamic range would be useful.

Preamplifiers can operate incorrectly for a number of reasons. Common problems are incorrect gain, non-flat response, weak batteries (for battery-powered preamplifiers), and excess electronic noise.

Secondary Amplifiers and Filters

Secondary amplifiers normally provide two functions: i) additional variable amplification (in increments of 1 to 3 dB); and ii) additional filtering (it is most convenient if these filters are of the plug-in variety). In the past, the basic design of the secondary amplifiers of commercial AE equipment often did not allow going down to frequencies below 20-30 kHz. This fact meant that expensive modifications were required to do AE monitoring on composites at low frequencies.

Sometimes it is useful to operate the preamplifier and secondary amplifier wide-band and use a variable filter. This approach is useful when signal propagation studies are being made at various bandpasses. The alternative is to purchase a large number of plug-in filters.

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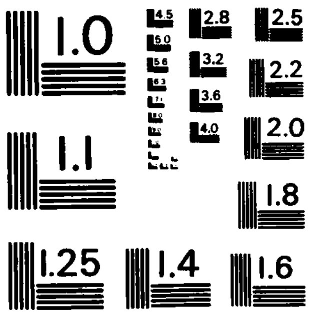

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Both filters and secondary amplifiers have limits on the maximum voltage that can be passed. Often, their maximum output voltages are on the order of 7-10 volts peak to peak. For larger voltages, saturation and/or clipping occurs in the same fashion as for preamplifiers.

The primary difficulties with secondary amplifiers and filters are: i) incorrect gain, ii) excess electronic noise and iii) non-flat response over the bandwidth.

Time Domains and Characterization of Analog AE Signals

Classically, an AE signal from a single AE event has an exponential increase followed by an exponential decay (see figure 2-1). From the point of view of AE equipment, the definition of an AE event depends on the analog voltage exceeding a pre-set or floating voltage threshold. When the voltage exceeds the threshold an AE event is said to have been sensed. Typical AE equipment can characterize the AE event in several ways (see figure 2-1): i) the peak voltage of the AE event; ii) the duration of the AE event (i.e., the time that the signal is above the threshold); iii) the rise time of the AE event (i.e., the time from the first threshold crossing to the peak voltage); iv) the time of arrival of the AE event (i.e., the time of day at which the first threshold crossing occurred or the time the threshold crossing occurred relative to the time at which another AE event occurred); v) the energy in the AE event during the duration; and vi) the number of counts of the event (i.e., the number of positive threshold crossings during the event). When AE is characterized by discrete AE events, then it is called burst type AE.

There is a second classical type of AE signal. This is called continuous AE. Continuous AE is distinguished from burst type AE by

the fact that there are so many AE events occurring over such a short time period that the AE events superimpose on each other in time such that it is no longer possible to distinguish discrete AE events. For continuous AE many of the parameters which are used to characterize burst-type AE no longer make sense. The typical characterization of continuous AE is the measurement of the rms voltage level. This approach gives a measurement of the energy rate of the AE out of the AE sensor. AE counts can also be measured for continuous AE. Usually, the counts are expressed as count-rate in this case. Peak amplitudes can be measured, but the real meaning of this measurement is not clear, since it will be a complex function of the number of AE events (and their individual amplitudes) which make up the continuous AE and the dead time (see explanation below) of the AE instrumentation.

Often, the AE observed in composites can be a combination of both burst type AE and continuous type AE. This type of AE requires a careful selection of AE equipment parameters such as threshold and dead time to obtain meaningful results. Often, the best characterization of such AE can be obtained using an rms meter which measures the energy rate of continuous AE and the energy in individual AE bursts (provided the bursts are sufficiently separated in time). The rms data can be particularly useful to determine the level at which the threshold of the AE system should be set.

A key parameter which the operator must select is the dead time of the AE system. The dead time is used to allow the AE equipment to know when one AE event is completed so that the system can be reset to be able to process another AE event. The dead time is the time increment during which if the threshold is not penetrated, then the AE

system concludes that the AE event is over. If the dead time is set at too large a value, then the AE system will measure more than one AE event as one event. If the dead time is set too short, then the AE system will measure one AE event as several events. For composites, since the AE event rate can be quite high, it is important to set the dead time quite short (particularly for computer based AE systems). Typically, choosing the dead time to be 10-15% of the typical event duration seems to give satisfactory results. For values less than this, the quarter-period of the nominal frequency in the AE bandpass should be calculated to make sure that the dead time is at least 8 to 16 times this value (i.e., 2 to 4 times the period).

In nearly every case, the AE event energy measured by commercial AE equipment is an approximation of the true energy which is defined by the equation

$$E \alpha \int_0^{t_d} \left\{ v(t) \right\}^2 dt \tag{2.2}$$

where E is the energy in the AE event, t_d is the event duration, and v(t) is the voltage as a function of time. Until such time as the equipment manufacturers provide, for their equipment, an explicit correlation curve for measured value vs. the true energy for real AE events in the bandpass of interest, it is best to consider the measured energy values as approximations. Note these energy measurements are measurements of the energy out of the AE sensor.

<u>AE Sources in Composites</u>

Before discussing specific AE sources in composites, it is important to point out that most sources of interest are stress driven. Stress driven means that AE is generated as a <u>response</u> of a specimen or

structure to applied stress and/or residual stresses which are present. Without stress no AE would be generated, since no stored energy would be available. Thus, the general picture of the generation of AE is: 1) externally applied or residual stress; 2) a local micro- or macro-damage or deformation mechanism; 3) a rapid change in the stress state caused by the local damage or deformation mechanism; and 4) stress waves generated by the local change in stress state. In some cases, AE is generated as a response to stress and time; e.g., when there is an incubation period after the application of stress before the deformation or damage mechanism occurs.

Before discussing sources of AE for composites, it is in order to define composite materials. Composite materials can be divided into three broad categories: dispersion strengthened, particle reinforced, and fiber reinforced [1]. In each category, the composite is made of a matrix material and a second-phase material distributed throughout the matrix.

Dispersion-strengthened composite materials have a small (0.01- to 0.1 μm diameter) and hard second phase (volume concentration <15%) dispersed throughout the matrix. These composite materials are distinct from precipitation alloy systems; for example, they are made normally by powder-metallurgy techniques, and the second phase does not go into solution when the material is heated near the melting temperature of the matrix.

Particle-reinforced composite materials are distinguished from dispersion-strengthened composites by larger dispersoid size (>1.0 μm) and increased concentration of the dispersoid volume (>25%). In addition, particle-reinforced composites are strengthened by the inherent

relative hardness (compared to the matrix) of the dispersoid and by dispersoid constraint of matrix deformation. This strengthening mechanism is different from that in dispersion-strengthened composites, where restriction of the motion of dislocations by the second phase provides the strength enhancement.

The distinct microstructural difference of fiber-reinforced composites is that the second phase (i.e., the fiber) has one dimension larger than the other two. This characteristic leads to anisotropic composite properties rather than the isotropic properties of the first two categories.

Since few AE results have been published on dispersion- and particle-strengthened composites, this section will emphasize fiber-reinforced composites. Only a few sentences will be devoted to the other two types of composites. The three main parts of a fiber composite are the fibers, the matrix, and the interfaces. The sources of AE associated with the fibers are: i) fracture, ii) cracking and splitting, and iii) plastic deformation. The sources of AE that originate with the matrix are: i) cracking, ii) crazing, and iii) plastic deformation. Interfaces can also lead to several sources of AE: i) interlaminar debonding, ii) fiber-matrix debonding, and iii) rubbing (e.g., fiber pull-out or relative motion of fracture or delamination surfaces). Figure 2.2 shows a schematic of a fiber composite and a listing of these sources. It is to be expected that these fundamental source events or damage mechanisms do not act in an isolated fashion. Hence, characteristic AE sources in fiber composites can be expected to be combinations of these sources.

Sources in dispersion-strengthened and particle-reinforced composites will be, in general, cracking of both phases and at the interfaces as well as plastic deformation. Plastic deformation will occur primarily in the matrix material with most AE sources being those that are present in metals.

Wave Propagation Aspects

In general, wave propagation is a complex subject even in homogeneous and isotropic materials. Since composites have neither of these characteristics, wave propagation for composites is particularly complex. The aim here is to give the reader a general understanding of key aspects which relate directly to practical AE testing of composites.

As in all AE testing, the stress waves generated by each AE event propagate through the composite and any other possible paths to the transducer. This propagation greatly influences the resulting electrical signal out of the transducer. Aspects of stress-wave propagation that significantly influence the electrical signals are: geometric spreading of the stress wave, losses due to material absorption of the stress-wave energy, direct and reflected paths from the AE source to the transducer, different modes and speeds of propagation of the stress waves along with dispersion of the stress waves, and scattering from "obstacles" encountered in the line of travel of the wave.

Geometric spreading is the loss in signal amplitude due to the fact that, as the wave travels away from the point AE source in a two- or three-dimensional medium, the total area of material through which the wave front is passing increases. Conservation of energy can be used to calculate the resulting change in amplitude. As a reference,

it is well known that for an infinitely thin flat plate the amplitude (not in the immediate vicinity of the source) is inversely proportional to the square root of the distance the wave front has traveled from the source. In real structures, geometric spreading does not always decrease the signal amplitude with increased distance of propagation. For example, in a spherical pressure vessel, geometric spreading is approximately proportional to $\sin^{-1/2} \theta$, where θ is the angle between a radius to the AE source and a radius to the center of the AE transducer. Hence, at 90° from the source the amplitude is smallest, but at 180° the theoretical amplitude approaches that near the vicinity of the source.

Losses due to material absorption of the stress-wave energy result in attenuation of the amplitude of the wave as it propagates. This attenuation is more severe for stress waves at higher frequencies and in viscoelastic materials such as epoxy. Analytically, this loss of energy by heat can be expressed by an exponential dependence on distance of propagation (the exponent depends on frequency). Material energy absorption is a major difficulty in monitoring the AE generated in fiber composites. To a certain degree this difficulty can be partially overcome by the use of a relatively low-frequency bandpass (e.g., 5 to 30 kHz).

Acoustic-emission stress waves in composites have several significant components that propagate at different speeds. Typically, two wave packets can be distinguished on the basis of wave speed: A generally lower-amplitude first arrival and a higher-amplitude second arrival. Depending on the relative amplitudes of these waves and the distance between the AE event and the transducer, this feature signifi-

cantly affects the AE signal out of the transducer. Also, for fiber composites depending on the orientation of the fibers,the wave speeds in the composite can vary for different directions of propagation of the AE waves. If the fibers are at several different directions, such as in many filament-wound vessels, then the wave speeds do not vary significantly with direction. But, if all the fibers are in the same direction, then the wave speeds in the direction of the fibers can be substantially higher (up to a factor-of-four difference, depending on frequency, for an unidirectional graphite/epoxy composite). It is also possible for part of the stress waves from a given AE event to propagate totally in a fiber. If this fiber happens to pass directly under a transducer, a completely unexpected path to the transducer is possible. Typically, in a fiber/epoxy composite with fibers in many directions, the actual composite wave speeds are dominated by the wave speeds through the epoxy matrix. This situation results from substantially slower speeds of propagation in the epoxy than in the fiber. All of the above propagation effects can substantially affect the use of arrival times at multiple AE transducers to locate the AE events. Later in this part, we will give an example of some of these effects. Note that the differences in path can cause propagation losses of peak amplitude, but not AE event energy.

Dispersion of AE stress waves in composites refers to propagation of different-frequency components at different speeds. The net result of dispersion is a spreading in the time domain of the stress wave as a function of distance traveled. This results in a decrease in peak

signal amplitude but not energy in the AE burst. This is the second reason why event energy does not attenuate as rapidly as peak amplitude.

Scattering is an inherent aspect of wave propagation in a composite. Energy is lost due to propagation of part of the energy in directions different than the line of travel of the wave. The second phase material (e.g., fibers) can be considered to be "defects" which cause scattering. This effect depends on the wavelength of the sound wave and the cross-sectional area of the "defects."

Because of all the complications noted above, the stress wave that reaches an AE transducer bears little resemblance to that which was generated at the AE source. For this reason it is very difficult to use frequency spectra to distinguish between different types of AE sources in a useful fiber-composite structure. In fact, for a repeatable source such as a pencil-lead break, the spectrum of the AE burst is different for the lead being broken at different locations on the composite part.

The fact that the peak amplitude can be greatly effected by signal propagation losses needs to be emphasized. This problem can only be minimized by the use of more AE sensors and/or a lower frequency bandpass (in a few cases, a waveguide can also be used effectively). The importance of minimizing this effect is due to the use of peak amplitude to distinguish source mechanisms in composites (more on this later) or to determine the severity of micro-damage in the composite. Wadin and Pollock showed that up to 45 dB in AE amplitude could be lost over 50 cm of propagation in a glass/epoxy composite [2], for steel the loss over an equivalent distance is 3-5 dB [3].

For certain applications of AE to composites, it is not necessary to use a low frequency bandpass. In fact, it is desirable to use a high frequency bandpass. This application uses signal propagation losses such that random flaw generated AE events do not propagate to the sensor with sufficient amplitude to be sensed. Hence, only events in the near vicinity of the sensor are sensed. This is desirable when the purpose of the AE study is to monitor the micro-deformation and failure mechanisms which are uniformly distributed throughout the composite. In this case, random flaw generated events only confuse the results.

There is another aspect of wave propagation that is important to discuss. This relates to AE signal durations. The AE signal duration is made up of two components: first, the ringing of the AE sensor; and, second, the paths of propagation of the AE signal before it is attenuated below the system threshold level. Often with a low frequency bandpass and a composite test sample which is not too large, the largest component in the AE event duration is the "ringing" of the stress waves in the test sample. Experimentally, these two components can be evaluated by looking at the time domains from lead breaks on the test sample vs. the domains for lead breaks on the face of the AE sensor.

Source or Flaw Location in Composites

Since the AE stress waves which are generated at a specific location propagate with certain velocities in all directions, by using more than one transducer, AE practitioners in composites have been able to locate the region or point of origin of the AE source event. Basically, the same techniques that are used to "triangulate" the epicenter

of an earthquake are used. This approach measures the relative arrival times of the AE event (from a specific AE event) at transducers which are located at several points on the composite. For relatively simple structures (e.g., rods or uniform thickness plates) with constant velocities of wave propagation in all directions (usually not the case in composites) simple calculations can be used to determine where the AE source (e.g., a growing flaw) originated.

Since more useful composite structures do not meet the above requirements (plus others to be discussed later), alternative techniques have been used in composites. The technique which has proved most useful is called area location. This technique has been implemented in two ways. The first approach makes use of the high signal propagation losses in composites. In this approach, a combination of frequency bandpass and AE sensor spacing is chosen such that only the sensor in the immediate vicinity of the AE source senses the AE event. Thus, using this technique, regions of the composite which are experiencing the most damage can be identified. This approach works best when there are a few known regions of relatively high stress in the composite. It does not work well when AE sources could be anyplace in the composite. In this latter case, either source events can be missed or the events can "hit" more than one sensor.

The second approach has been developed to overcome the weakness of the first. This approach requires more sophisticated AE equipment and a lower frequency bandpass and/or more closely spaced AE sensors. For each AE event the arrival time at the AE sensors which it hits (a sensor is hit when the signal from the AE sensor has sufficient amplitude to be above the set voltage threshold) is recorded as well as the

peak amplitude at that sensor. Then using the general principles that the first hit sensor and the sensor with the highest peak amplitude are the sensor closest to the AE source location, each particular AE event can be assigned to a certain region. Again, the cummulative results would indicate the region on the composite structure where most damage was taking place, say during a proof test.

The classical techniques of source location (mentioned above) which result in a much more precise location have not yet been fully implemented in most composites. The status and the reasons for problems in this area will be discussed further in Part 4 of this report.

The Kaiser Effect/Felicity Ratio

Since there is a good deal of confusion concerning these terms for composites, the author's own current definition of these terms will be given, followed by a discussion of variables which seem to be important. A more detailed discussion of the current state of these terms for composites will be deferred until Part 4.

The more general term is the Felicity ratio. The Felicity ratio is the numerical value which results when the load at which "significant AE" begins on a subsequent cycle is divided by the maximum load during the previous cycle. The term "significant AE" needs further explanation. At the current time, there is no fixed definition of "significant AE." Hence, most AE practitioners use their own past experience. The factors that the AE practitioner looks for are the numbers of AE bursts as a function of certain load increments compared to the numbers of events over the same load increment during the prior loading and the signal levels of these AE bursts compared to those during the initial loading. The CARP recommended practice [4] suggests

three guidelines for the determination of the onset of significant AE:

1) More than 5 bursts of emission during a 10% increase in load;

2) More than 20 counts during a 10% increase in load;

3) Emission continues at a load hold.

There are a number of variables which can effect the value of the Felicity ratio: loading and unloading rates, time at peak load, AE system sensitivity, time between load cycles, stress state during loading, AE source mechanism, test or storage (between load cycles) environment, and proof load level relative to the expected ultimate strength. Materials which have rate dependent properties have the largest effects with most of these variables. Many fiber composites with plastic matrices have this characteristic.

The Kaiser effect is said to hold when the Felicity ratio is $\geq$1.0. If the Felicity effect is $\leq$1.0, then the Kaiser effect is said to be violated. Hence, it is clear that when the Kaiser effect holds, no new AE sources have operated and no reversible AE sources were present during the subsequent load cycle of the specimen being tested. But, if the Kaiser effect is violated, then either or both of these cases has occurred.

<u>Factors of Significance in AE Data</u>

There are six basic factors which must be taken into account when determining the significance of the AE which has been recorded during a test of a composite. First, since AE is generated as a response of a specimen or structure to stress, the stress levels at which the AE events occur are of importance. Normally, the lower the stress at which AE events occur, the poorer the structure. The second factor is the energy (or amplitude) of the AE bursts. The usual conclusion is:

the higher the energy of an AE event, the larger or more significant the damage to the specimen. Most AE data indicate large increases in AE amplitudes near the failure level of composites. Third, the total numbers of AE events is also of significance. Normally, the larger the number of AE events, the greater the damage to the composite. Fourth, the location of the AE sources is of key significance for composites. Composites often have a considerable number of AE events which originate at random locations throughout the specimen. These random location events often have little or nothing to do with the strength or life of the structure. Of much greater importance are AE events which originate at the same location. These AE events are indicative of a growing region of damage and of potential serious damage to the structure. Fifth, the value of the Felicity ratio is also a significant factor in AE data for composites. Normally, the lower the value (i.e., <1.0) of the Felicity ratio, the poorer the composite sample. Sixth, the rate of accumulation of AE events as a function of increasing stress (or time) is significant. When the slope of such a curve changes significantly, or becomes exponential, the rapid growth of damage indicates changes in source mechanisms or flaw growth becoming unstable as a percursor to total failure. Similarly continued AE with time at a load hold implies creep processes which may be becoming unstable.

The interpretation of the significance of AE data for a specific instance is largely a matter of experience. The key experience is gained by monitoring good vs. bad specimens. This fact points to the reason why the earlier sections in this part placed such an emphasis on doing identical AE tests. In this section on significance, we have

ignored what is probably a key factor, namely the identity of the source mechanism which produced the AE. Since there are currently no standard techniques which can be used to identify the source for a given AE burst, we can't as yet include this as a factor of significance. Future developments in the AE field may result in such techniques. These techniques could be very useful for composites such as fiber reinforced composites where fiber failures are often of much greater significance than matrix cracking.

In situ Calibration of AE Tests

Since there is a large emphasis on comparison of AE data from one test to another, it is important to adopt an *in situ* calibration technique. Such a technique will allow for checking the following: i) propagation characteristics of the test specimen and associated test fixturing; ii) the efficiency of the AE couplant; iii) the sensitivity of the AE sensor; and iv) the operation of the preamplifier and other AE equipment. By adopting certain minimum and maximum outputs of the calibration signal, the AE test can be certified as identical for each composite structure.

There is a further reason for using an *in situ* calibration. An *in situ* calibration checks every aspect of the AE test. This is important to do because if something is wrong with the AE test, it is not possible to repeat the test as most AE which is generated is irreversible, and so the first load cycle has unique AE data which can never be repeated.

To date, the most convenient simulated AE source event for calibration purposes is the fracture of pencil lead in contact with the test specimen. The rapid release of the Hertzian contact stresses

simulates the $\Delta\sigma_{ij}(\underset{\sim}{x}, \Delta t, \Delta V)$ of a real AE event. The best approach is to build a mechanical lead breaker so that each lead break takes place at the same location and under the same geometric conditions. By building a load cell into the lead-breaker, the load at which the lead breaks can be measured. This assures that the lead break used for calibration was at the normal load. The length of lead must be controlled as well as rebounds of the broken lead against the test part. The lead breaker must be isolated with respect to wave propagation from the test specimen and AE sensor. This isolation is necessary so that AE generated in the lead-breaker does not reach the AE sensor. Typically best results occur with 0.3 mm or 0.5 mm diameter 2H lead. Since the lead sometimes fractures in other than normal fashion, usually 3 or 4 breaks are used. The first and last few breaks from a length of lead should not be used for calibration.

Extraneous AE

It is a relatively simple procedure to attach an AE sensor to a composite, load the composite, and obtain AE data. Along with the AE data of interest (i.e., that which originates from the specimen as it is loaded) there may be considerable amounts of AE from extraneous sources. Some typical extraneous sources of AE are: 1) AE from the loading apparatus or test fixture, 2) AE from the test machine or specimen grips, 3) AE from ground loops, 4) AE from other machinery in the test environment, 5) AE from voltage spikes or stray electromechanical signals, 6) AE from strain gages, and 7) AE from unexpected sources. Since it is often necessary to go to a lower frequency bandpass with composites to overcome signal propagation losses, extraneous noises can be expected to be present in greater amounts for composite

testing. But, this situation does not necessarily imply that the AE signal to extraneous noise ratio will be worse for a low frequency bandpass. The reason for this is that at lower frequencies the amplitudes of the real AE signals are considerably larger.

There is one fundamental way to prove that significant AE from extraneous sources is not present (at the particular AE sensitivity used) in a particular test. The technique is to replace the test specimen with a dummy specimen which is known not to emit AE under load. Then the test is run with the dummy in place and any AE which is generated will be from extraneous sources. It is possible to check for most extraneous AE sources for test specimens/structures which have a high Felicity ratio (i.e., ≥ 1.0). In such a case, the test sample can be cycled twice (to prove the Felicity ratio is ≥ 1.0), then it can be completely removed from the test fixture, reinstalled and tested again. If the Felicity ratio is greater than or equal to what it was before, then all but a few possible sources of extraneous AE have been shown to be insignificant at the AE sensitivity that was used. It is an important step to completely remove the test specimen from the test fixture, and also, to tear down the test fixture if that is normally done between or at the end of a set of AE tests. Often, unexpected extraneous AE sources will be uncovered by such an approach. The use of the Felicity effect does not check all potential extraneous AE sources. For example, with "tab type" composite tensile samples, the use of the Felicity effect would not prove that the adhesive between the tabs and the specimen was not a source of extraneous AE.

Extraneous sources of AE can often be eliminated by better design of the test set-up or the test environment. Also, absorbing materials

can be used or the AE equipment can be operated at less sensitivity. In some cases, it may be necessary to redesign the test specimen or the test fixturing, or to test at a different location or time of day. In an extreme case it may be necessary to conclude that AE in its present state of development is not an appropriate test. In Part 4 we will discuss progress made towards using electronic or other techniques to recognize and eliminate extraneous AE.

Control Checks on AE Testing

In production testing or other regular testing of composites with AE, there are certain measurements which can warn the responsible person that all is not correct for the AE test. A simple approach to this is to use so-called "running charts." These charts are historical plots of some key measurements which relate to the overall health of the AE system. When steady or step changes occur in these charts, then it is time to fully check out the AE test system or test technicians. Typical measurements which might be recorded on such charts are: 1) load at which the lead fractures; 2) the AE peak amplitude from the lead fracture event, and 3) the electronic rms value of the background noise level.

It is also necessary to periodically check the AE electronics as well. Electronic equipment does suffer breakdowns, and these breakdowns are not always characterized by a complete loss of functions. AE equipment, particularly computer based systems, can function quite nicely, but at the same time be making incorrect measurements [5].

Additional Instrumentation

In addition to what is normally sold as AE equipment, there are

several electronics instruments which are quite valuable. These can be used both to make decisions on instrument level settings of the AE equipment and also to diagnose problems with the AE data.

Typically, these additional pieces of equipment are a combination of a transient recorder and an oscilloscope, a variable oscillator with variable dB attenuator, and a true rms meter (if it is not already a part of the AE system). The scope-transient recorder can be used to determine the levels to set such parameters as the dead time and the threshold of the AE system. It can also be used to determine the type of AE which is present (e.g., burst-type vs. continuous). The oscillator can be used to check gains and bandpasses in combination with the rms meter. The scope is also useful to check for extraneous electronic noise sources such as ground loops.

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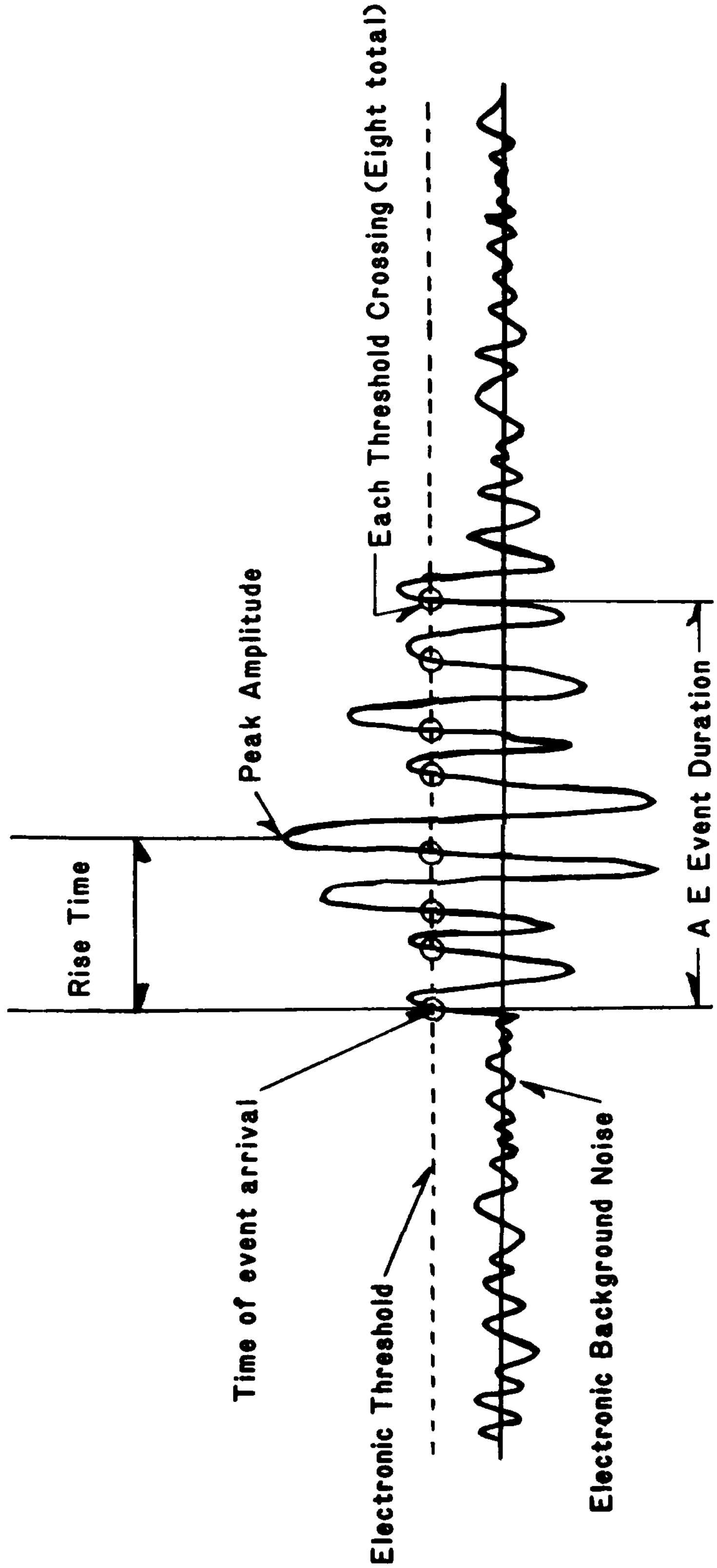
Figure Captions

Figure 2.1 Classical AE burst event.

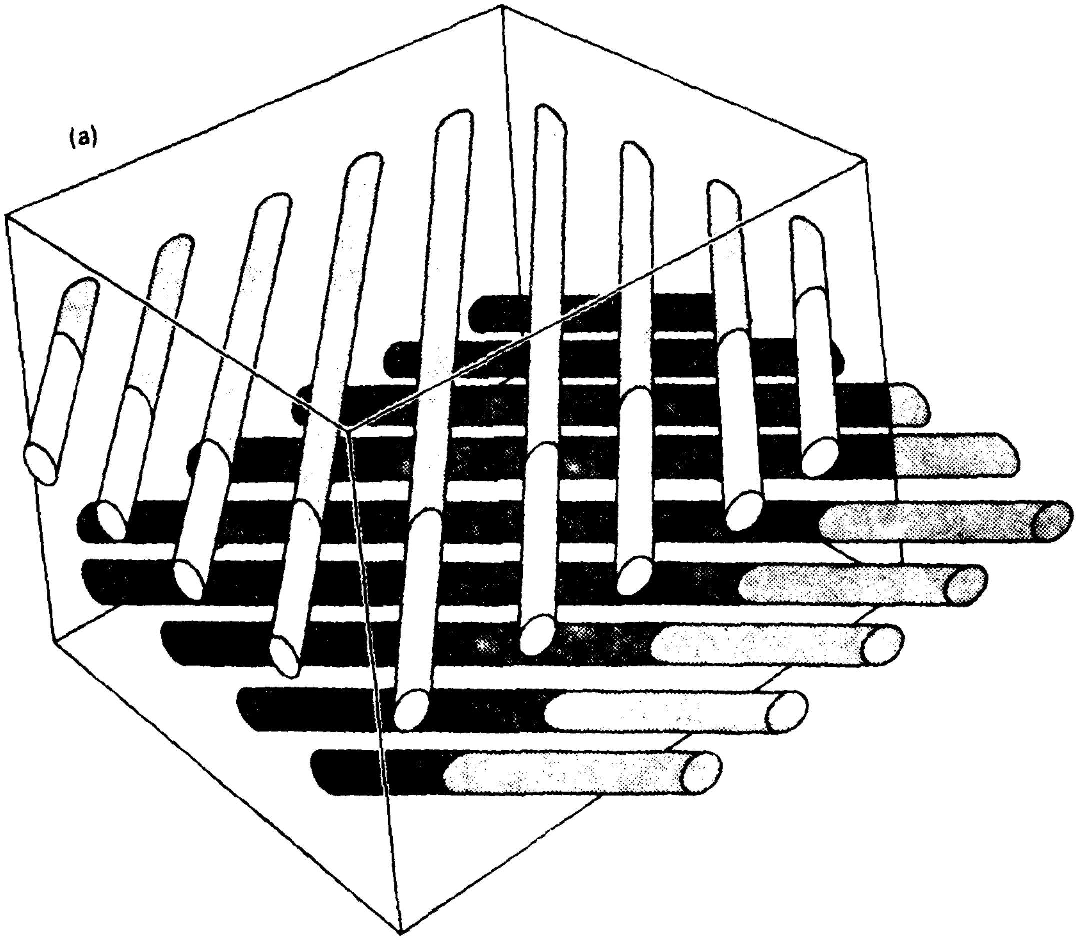
Figure 2.2 Schematic of fiber composite a); and list of AE source mechanisms b).



Each Threshold Crossing (Eight total)
Peak Amplitude
Rise Time
A E Event Duration
Time of event arrival
Electronic Threshold
Electronic Background Noise

Fig. 2.1

(a)



(b)

Fiber
- Fracture
- Cracking & splitting
- Plastic deformation

Matrix
- Cracking
- Crazing
- Plastic deformation

Interfaces
- Interlaminar debonding
- Fiber-matrix debonding
- Rubbing (pull-out)

Fig. 2.2

Part 3 - A Representative Survey of Applications of AE to Composites

The purpose of this chapter is to survey the typical applications of AE which have been developed for composites. These applications will be divided into two broad catagories. The first of these (and to date the largest based on number of reports) will be called materials studies. Included in this category are applications which use the unique capabilities of AE to monitor entire volumes of test samples for characterization of micro- or macro- damage processes which occur as a function of load or some other loading which stresses the sample. The second category will be called quality control and/or nondestructive evaluation (NDE). Included in this category are applications in which AE has been used to make a decision about the quality or strength of a particular part or structure. We have excluded from this category the development of NDE techniques where real parts or structures were not used but instead test coupons or other non-real parts were used. These development tests will be covered in Part 4 of this report.

Two comments are in order at this point. The first is with respect to the use of the term NDE. To cause AE to be generated it is necessary to load the part. Further, in most cases if AE is generated, then some micro-damage has occurred. Thus the use of the term NDE might be questioned. With AE testing our use of the term NDE has the following meaning. The loading of the part is such that for good parts the intended use of the part is not impaired by the AE test. The second comment is that it is not the intent to describe in any detail the various applications. Instead, we will attempt to survey the broad diversity of applications with the intent that the readers will obtain the original paper or report on subjects that are of particular interest to them.

I. Materials Studies

Application to Time Dependent Studies

Rotem and Baruch (1974) used AE monitoring to characterize damage accumulation as a function of time in unidirectional glass/epoxy samples under load holds. They also used AE to characterize damage which occurred with proof cycles interspersed during the load holds. Rotem (1978) showed by AE that the damage during a tensile test of unidirectional E-glass/epoxy depended on the strain rate. He observed an increase in the number of AE events when the strain rate decreased (see figure 3.1). He noted that these strain rate effects did not occur with graphite fibers in the same epoxy. Ryder and Wadin (1979) used AE to track the initiation of damage and the progression of damage in graphite/epoxy laminates during tension-tension fatigue testing. Eisenblatter et al. (1974) showed during fatigue of glass reinforced composites that the damage growth as characterized by the summation of counts showed high rates of damage for the early fatigue cycles and the fatigue cycles near failure. Between the beginning and the end, the damage rate was much lower. Fuwa et al. (1975) compared damage progression in graphite/epoxy and glass/epoxy. They found very low damage rates after the first few cycles in graphite/epoxy even at about 90% of the failure level. For glass/epoxy the AE data indicated that damage continued even when it was cycled at about 30% of the failure level. Laroche and Bunsell (1980) used AE to obtain damage accumulation as a function of load holds at different levels for graphite/epoxy. They concluded on the basis of the AE data that the total damage sequence is independent of load history, but that the time to arrive at a given

damage state depends on the load history. Williams and Reifsnider (1977) showed that by monitoring AE (above 50% of the peak load) during fatigue of boron/aluminum and boron/epoxy samples with drilled holes that a good correlation of the cummulative total of AE counts and the compliance change was obtained (see figure 3.2). This result led them to conclude that the same physical mechanism which caused the AE also caused the compliance change. Lark and Moorhead (1978) used AE to follow and characterize damage progression during sustained loading tests to failure of Kevlar/epoxy pressure vessels. Detkov (1976) showed that the count rates observed in tension testing of unidirectional fiberglass rings increased with increasing strain rate. It should be noted that this result seems to be different than Rotem's above. Fowler's (1977) studies indicate that AE generated during a hold test of glass/plastics shows how stable or unstable a structure is.

Application to Impact Studies

Ochiai et al. (1982) correlated characteristics of the load vs. time curve with the corresponding AE during instrumented impact of plates of graphite/epoxy and sheet moulding compound (see figure 3.3). They observed with the proper choice of AE system sensitivity that no AE was observed when no impact damage occurred and AE was observed when damage did occur. This led them to observe that a certain level of impact of a defective plate would produce AE, while the same level impact would not produce AE on a non-defective plate. Bailey et al. (1977) showed that AE could be used to detect prior impact damage in graphite/epoxy samples at low stress levels during subsequent tensile tests.

Application to Correlation of Damage with Stress Level

DeCharentenay and Benzeggagh (1980) and DeCharentenay (1979) demonstrated, using AE to monitor Mode I and Mode II delamination experiments, that it was possible to distinguish three separate stages of delamination: no cracking and initiation, micro cracking, and stable growth and delamination (see figure 3.4.). Old and Charlesworth (1976) showed that AE could be used to determine the stress level at which transverse cracks in Nb_3Sn fibers in a copper matrix began. Fuwa et al. (1975) used AE monitoring of fiber bundles of graphite with no matrix, graphite/semi-cured matrix, and fully cured graphite/epoxy to develop a theory of failure for the composite. A number of investigators have shown a correspondence between a knee in the stress vs. strain curve and the start of AE (see figure 3.5) or a change in the AE behavior [see Takehana and Kimpara (1972), Henneke and Herakovich (1973), and Kimpara et al. (1976)]. Lloyd and Tangri (1974) used AE to monitor fracture processes as a function of stress in a short fiber composite Mo/Al_2O_3. Mazzio et al. (1973) used AE to keep track of graphite fiber failures in model composites subjected to tensile loading after various thermal cycles. Harris et al. (1979) showed during a tension test interrupted with load or displacement holds, that when the test was resumed the damage pattern quickly goes back to that of a non-interrupted test. Guild and Adams (1981) used AE to detect first damage in four-point bending of beams. Swindlehurst (1978) used AE monitoring of tension of a tungsten/copper composite to monitor stress levels for plastic flow of the copper matrix (by continuous AE) and fiber fractures (by AE bursts) (see figure 3.6). Swanson and Hancock (1971) used AE to distinguish when filament fracture began relative to

plastic matrix flow for boron/aluminum unidirectional tension samples tested at 0°, 90° and 30° to the fiber axis. Grandemange and Street (1976) used AE to determine the exact stress level of boron fiber failures in notched boron/aluminum fracture specimens. These AE results allowed them to perform certain calculations. Rathbun et al. (1971) used AE to experimentally determine the loading level above which a glass/epoxy composite vessel suffered significant structural damage. Hutton (1975) determined the stress level where fiber failures begin in nylon/polyurethane with AE monitoring.

Application of Correlation of AE with Other Measures of Damage

Sims et al. (1977) for interrupted tension tests of $0/90^{\circ}$ glass/epoxy laminates correlated cummulative AE counts with increasing transverse crack area in the 90° plys (see figure 3.7), decreasing dynamic modulus, and increasing damping. Harris et al. (1979) showed a correlation of cummulative AE counts and changes in resonant frequency. Guild and Adams (1981) showed for 0° beams that the damping changed after significant AE occurred. Brown (1975) showed the drop in resonant frequency corresponded to increasing summation of AE counts. Fitz-Randolph et al. (1972) showed a correlation of the summation of AE counts and compliance for bending of a boron/epoxy notched beam. Fitz-Randolph (1971) showed that the AE counts during a load drop are directly proportional to the strain energy released by the material fractured during the crack extension which produced the load drop.

Application to Cure Studies

Phillips and Harris (1980) compared the AE during subsequent tensile tests for chopped strand mat/polyester cured at two different temperatures. There were about two times as many AE events for the composites cured at the higher temperature which had a more brittle matrix. Hahn (1976) used AE to show the effects of cure induced residual stresses. He monitored with AE a sample in tension for two cycles at room temperature showing that the felicity ratio was approximately one. He then took another sample and loaded it to the same level for two cycles. The first cycle was at 455° K and the second cycle was at room temperature. He observed that the felicity ratio was considerably less than one. He attributed this to the fact that the residual stresses present at room temperature caused new damage to occur on the second cycle. It may be that this new damage was due in part to differences in the modulus and elongation of the matrix at the two temperatures. Hinton et al. (1981) used AE to monitor the cure process of flat laminates of both Kevlar and glass (see figure 3.8). They believe the first AE in the cure cycle is due to outgassing of the resin and that the latter activity is caused by cure shrinkage of the resin relative to the fiber. They observed higher amplitudes of AE and more AE events in Kevlar composites compared to glass composites. Houghton et al. (1979) used AE to monitor cure cool-down of E-glass/epoxy. They found that a fast cool down from peak temperature led to large and frequent AE bursts while a slow cool-down resulted in small and infrequent AE, as well as a slightly lower tensile strength (see figure 3.9).

Application to Differences in Matrix Materials

Phillips et al. (1982) showed for chopped strand mat tensile samples that the amplitude distributions were different with respect to locations of peaks for resins with different elongations (see figure 3.10). McGarry et al. (1977) used audible AE to show the reduction in matrix cracks for bulk moulding compound material subjected to bending when increasing amounts of liquid rubber were added to the polyester matrix. As the fracture properties improved, the AE from the matrix cracking source mechanism decreased substantially. Hamstad and Chiao (1973) showed for both Kevlar and graphite pressure vessels that the AE begins at a higher pressure for less rigid epoxies. Later, Hamstad (1981) showed for Kevlar/epoxy pressure vessels that a flexible high elongation epoxy system resulted in the disappearance of the high amplitude early AE peak which occurs for stiff and low elongation epoxy systems (see figure 3.11). He also showed that when the pressure vessels with the stiff epoxy system were tested at an elevated temperature where the epoxy became flexible that the early peak again disappeared. Norwood and Millman (1979) showed, based on AE data, that the strain to first matrix damage (i.e., initiation of AE) is greater for more flexible resin systems in glass reinforced polyester under tensile loading of samples. Hamstad and Chiao (1974, 1976) showed that the amount of early AE in Kevlar/epoxy cylindrical pressure vessels could be used as an indicator of the dependence of burst strength on the choice of matrix material (see figure 3.12).

Application to Differences in Second Phase (Usually Fibers)

Holt and Worthington (1980) showed under tensile tests of unidirectional samples that glass/epoxy results in the generation of much more AE than graphite does with the same epoxy system. They also observed that the graphite/epoxy system fails without showing the same warning of impending failure which the glass/epoxy shows. Fuwa et al. (1976) earlier had reported this lack of warning for graphite/epoxy rings and pressure vessels. Carlyle (1978) saw in graphite/epoxy angle-ply samples during tension testing a sudden reduction in AE and then a rapid rise just before failure. Pattnaik and Lawley (1973) observed in directionally solidified $CuAl_2/Al$ that when the "fibers" are coarsened by heat treatment that the size of the individual AE bursts increased. Grenis and Levitt (1975) observed for boron/aluminum that the unidirectional composite goes to failure much more gradually with many more total AE counts than graphite/aluminum does even though in a given cross-section there are a lot less boron fibers than graphite fibers due to the larger diameter of the boron fibers. Crump and Droge (1979) studied the effect of increased glass content under tensile testing. They found that large amplitude events occurred at a lower percentage of the failure stress and the summation-of-counts curve exponentialy increased at a lower percentage of the failure stress as the glass content increased (see figure 3.13). Bunsell et al. (1974) showed by measuring the AE energy at fiber failure of Kevlar, glass, and graphite that Kevlar fibers fail by a different mechanism than the other two fibers. Fowler and Gray (1979) showed with AE that the first damage in a glass reinforced plastic occurs at a lower stress with increased glass content. Hamstad (1973) showed with

AE that graphite/epoxy cylindrical pressure vessels failed in a very brittle fashion compared to Kevlar/or glass/epoxy vessels. Arrington and Harris (1978) used AE to study the effect of a hybrid composite made of two different graphite fibers. They found more AE was generated by the hybrid than either fiber alone.

Application to Interface Studies

Rothwell and Arrington (1971) used AE to detect debonding between single glass fibers and the matrix material. The use of AE allowed them to distinguish three different ways in which debonding occurred. Corle et al. (1961) in a very early study used a microphone to detect when the bonds between fibers in paper fail under tension testing. This technique was the only approach which would allow them to keep track of bond failures for paper specimens with high fiber volumes. Buhmann (1975) demonstrated that AE could be used to optimize glass fiber finish such that the first matrix cracks occurred at a higher strain level. This could be done because the initiation of AE in glass/plastic pipes corresponded to the first matrix cracks which would allow gas to leak through the pipe walls.

Application to Dimensional Stability

DeLacy and Dharan (1982) used AE to study matrix stability of graphite/epoxy under temperature cycling. They examined effects of changes in temperature during cure as well as thermal cycling. Eselun et al. (1979) earlier had shown in graphite/epoxy a correlation between the summation of AE activity and expansion or contraction caused by temperature changes (see figure 3.14). They reported that the onset of temperature induced cracking could be determined by the onset of AE.

Application to Environmental Effects

Niesse (1979) showed that the AE in subsequent flexure tests of various E-glass/vinylesters showed the effects of chemical degradation upon the test samples. Graham (1977) was able to distinguish wet from dry graphite/epoxy samples subjected to four-point bending on the basis of the AE generated. He found differences in the initial slope of the amplitude distribution as well as in the average amplitude.

Application to Studies of Orientation Effects

Johnson and Jackson (1982) used AE to demonstrate that damage accumulation varies with the orientation of specimens from oriented short glass fiber/urethane samples. Fowler and Gray (1979) showed with AE that a random glass reinforced sample suffers damage at lower stresses than unidirectional samples. Harris *et al.* (1979) showed damage accumulation varied considerably for 0^{o}, 45^{o}, and 90^{o} samples of E-glass/epoxy tested in tension (see figure 3.15). Barnby and Perry (1976) showed AE gives a warning of imminent failure in a cross-ply glass/epoxy, but that the same warning was not present in unidirectional samples of the same material.

Application to Study of Differences in Materials

Phillips and Harris (1980) showed that there were significant differences between a variety of glass/plastic laminates in that damage accumulation as a function of load varied considerably. Brown and Mitchell (1980) tested two different fibers in two different matrix systems and found distinct differences in amplitude distributions at certain percentages of the failure load levels (see figure 3.16).

Miscellaneous Applications

Nomura et al. (1980) used AE to monitor the transition from super conductive to normal conductive behavior in a NbTi/Cu composite. They were able to thus determine the true critical current. Buhmann (1975) showed AE could be used to optimize fiber angles in pipes so as to increase the strain level at which first matrix cracks occurred. Ahlborn et al. (1973) used AE to detect first crack growth in notched glass/epoxy samples. Hamstad (1972) used AE results to explain the difference in failure level between glass/epoxy bottles filament wound with interspersed compared to non-interspersed winding patterns. Hamstad (1972, 1973) showed AE could be used to more easily design the most efficient (strength to weight ratio) cylindrical, filament-wound pressure vessels for both glass and Kevlar. Ansell and Harris (1980) used AE to monitor damage processes in a natural composite, namely wood. DeCharentenay et al. (1980) used AE for the detection of first delamination in fatigue of short beam shear. The number of cycles corresponding to first AE was used to develop an SN-curve for this type of failure (see figure 3.17).

II. Quality Control or NDE Applications:

Test Standards or Recommended Practices

One document has been completed for tanks and vessels. It is entitled "Recommended Practice for Acoustic Emission Testing of Fiberglass Reinforced Plastic Tanks/Vessels" [1982]. This document provides acceptance and rejection criteria for tanks/vessels based on the AE test results. It was prepared by the Committee on Acoustic Emission from Reinforced Plastics (CARP), a Working Group of the Corrosion-Resistant Structures Committee of the Reinforced Plastics/Composites

Institute of the Society of the Plastics Industry (SPI). This document was adopted in 1981 and widely published in 1982. It was considered by the ASTM Committee E-7 in January of 1983.

Four other documents are in draft stages. The first, "Specification for Down Hole Tubing" (reinforced thermosetting resin) was in the fourth draft stage as of August 1982. It is being prepared by an ASTM Task Group on FRP Tubular Goods under the auspices of ASTM Committee D-20 on Plastics. This document defines an AE test which determines the maximum tension and pressure loads for rating of the pipe according to an AE criterion.

The second, entitled "Recommended Practice for Acoustic Emission Testing of Reinforced Thermosetting Resin Pipe" is being prepared by CARP. This document was in its fifth draft as of August 1982. The AE test establishes acceptance or rejection criterion for lined or unlined pipe, fittings, joints, and piping systems.

The third document, entitled "Personnel Qualification and Certification In AE Testing of FRP Equipment" provides guidelines for the establishment of a qualification and certification program for AE test personnel. This document is also being prepared by CARP.

The fourth document, on the use of AE to test bucket-truck fiberglass and metal components, is being prepared by a task force of ASTM Committee F-18. This document is in a preliminary draft stage.

NDE of Low Performance Tanks/Vessels

Since a recommended practice is already approved in this area, the reader is referred to the literature by Fowler *et al.* (1979 (a), 1979 (b), 1980) for more documentation of both the basis for the recommended practice and statistics on the numbers of tanks/vessels tested.

NDE of Pipes/Fittings/Joints

Wolitz et al. (1978) showed the use of AE to pick out flawed pipes of glass/epoxy at about 40% of their normal strength based on changes in the amplitude distribution because of the occurrence of proportionally more high amplitude events. Schwalbe (1978) reported a study of a series of flaws in 60° glass/resin filament wound pipes. He studied two classes of defects: i) Localized defects - 1. concealed cuts in the tube wall, 2) knotted rovings, 3) missing rovings over the whole length, 4) impact damage; and ii) Uniformly distributed defects - 1. unimpregnated layers, 2. flexibilized resin, 3. low modulus glass (i.e., E-glass). He proof tested the pipes to 15% of their normal strength and found that two AE techniques had to be used to pick out pipes which suffered a degradation of more than 10% from the unflawed pipe strength (see figure 3.18). The reasons why two techniques were necessary were: 1) localized defects lead to few additional AE events compared to the number of randomly distributed events and hence these defects can only be detected if source location is used; 2) distributed defects don't show up in source location data, but they contribute a significantly larger number of events than the random events (for unflawed pipe) so that summation of events can pick out such flawed pipes. Fowler and Scarpellini (1980 II) noted that for pipes with joints having excess cement that the first cycle AE must be ignored since the cracking of the joint cement causes a lot of AE not related to the structural integrity. They also pointed out the need for sensors on each side of a joint due to severe attenuation across the joint. In a more extensive study of AE for NDE of pipes and joints, Fowler and Scarpellini (1982) concluded that except for the joints the

same criterion used for composite tanks could be applied. They found different AE criterion were needed for joints depending on the type of joints. For example, they found a true mean square (TMS) voltmeter was useful for detecting delaminations and cracking in joints.

NDE and/or Quality Control of High Performance Composites

Green *et al.* (1963;64) correlated an average acceleration amplitude over the pressure range of 100-600 psig from accelorometers located near the potential failure location to the eventual failure pressures (about 1200-1450 psig) such that failure levels could be predicted for large filament wound glass/epoxy rocket motor cases (see figure 3.19). Lingenfelder (1974) developed a correlation between the onset of AE (defined by AE greater than 4 counts per 1000 lb. increment) and the failure level for graphite/epoxy panels made from tape (see figure 3.20). It is to be noted that this approach did not work for the same panels made from cloth. Jessen *et al.* (1975) showed for intentionally different Kevlar/epoxy motor cases that the averaged AE felicity value (from all sensors) from all rms channels correlated with the failure level for a proof to 40-45% of expected failure level. It should be noted that both the Green *et al.* and Jessen *et al.* approaches used very rapid pressurization rates of the order of 100-200 psi/sec. Stinson and Lengel (1980) recorded the number of AE counts from 10 sensors on an asbestos mat/phenolic hemispherical shell during holds at about 55% of the failure level. They found for two shells, which were later found to have cracks in the flange area, that a large number of counts were recorded during holds on the first and second load cycles compared to good units (see figure 3.21). Hamstad (1973) showed that graphite/epoxy pressure vessels wound with frayed fiber could be

distinguished by a large amount of early AE compared to that from vessels wound with non-frayed fiber. Hamstad (1980) showed that quality control of the filament winding process could be maintained by obtaining an AE rms signature during a proof test to 20-30% of expected failure level for Kevlar/epoxy pressure vessels (see for example figure 3.22). Hamstad (1981) demonstrated the use of the AE to accept or reject graphite/epoxy structural domes. Acceptance or rejection was based on the number of large energy AE events during a proof test to about 66% of the expected failure level. Liu et al. (1982) developed a technique to correlate the pressure of the first AE peak to the final failure level for glass/epoxy pressure vessels (see figure 3.23). This technique was successful for vessels which did not have a local defect which controlled the failure location.

Application to Composite Booms and Bucket Trucks

Although there is little information available in the published literature, a number of utility companies use AE monitoring of proof tests of composite booms at scheduled intervals. It was shown for both fiberglass coupon specimens and actual fiberglass booms that the Felicity ratio drops below 1.0 at about 50% of the remaining strength (McElroy, 1980). Thus, AE can be used to determine the residual strength of such booms. Since it is possible for damaging overloads to occur between scheduled inspections, the use of on-board AE monitoring systems has been advocated (McElroy, 1980). These AE systems alert responsible individuals that damage loads have occurred during use in the field so that appropriate inspections can be undertaken.

Figure Captions

Figure 3.1 Effects of strain rate on AE events in tension test of unidirectional E-glass/epoxy composite [247].

Figure 3.2 Correlation between summation of AE counts and compliance for boron/epoxy composite in tension-tension fatigue [307].

Figure 3.3 Load and AE vs. time for impact which causes material damage on graphite/epoxy composite [222].

Figure 3.4 AE results during three stages of Mode I delamination of glass/epoxy composite [58].

Figure 3.5 AE count rate for boron/epoxy reinforced aluminum. AE is first detectable at the change in slope (knee) in the stress vs. strain curve for a laminate composite [162].

Figure 3.6 Burst AE (from fiber fractures) and continuous AE (from matrix deformation) for a tensile test of a composite made from a single tungsten fiber in a copper matrix [285].

Figure 3.7 Correlation between summation of AE and transverse crack area for tensile test of a $0^{o}/90^{o}$ glass/epoxy laminate [268].

Figure 3.8 AE and ion graphing obtained during the temperature and pressure cure cycle of an E-glass/epoxy laminate [167].

Figure 3.9 The effect of rate of cool down from cure for E-glass/epoxy laminate [170].

Figure 3.10 Differences in AE amplitude distribution for tensile tests of chopped strand mat laminates with two different resins. Resin A has a lower elongation than resin B [231].

Figure 3.11 For Kevlar 49/epoxy pressure vessels during proof testing: i) very high amplitude AE is present in the stiff matrix composite; ii) an early peak of AE is present in the stiff system versus a gradual increase in AE in the flexible system [155].

Figure 3.12 The amount of early AE for a Kevlar 49/epoxy pressure vessel with different resins has an inverse correlation with average failure levels. Average failure levels: 1 - 18.3 MPa; 4 - 16.0 MPa; 7 - 14.8 MPa [146].

Figure 3.13 Data showing that increased glass content results in AE beginning at a lower percentage of the failure level [107].

Figure 3.14 AE activity correlates with coefficient of thermal expansion for temperature changes of a composite tube [77].

Figure 3.15 The accumulation of AE counts (for a non-woven glass laminate loaded in tension) versus stress depends on specimen orientation [0^{o}(O), 90^{o} (△), 45^{o} (□)] [158].

Figure 3.16 Changing fiber material changes the tensile amplitude distribution data for vinylester composites [31].

Figure 3.17 Fatigue S-N curve for shear failure based on AE detection of shear failure [60].

Figure 3.18 Detection of flaws in glass/polyester tubes. A: Using source location. B: Using a distinct increase in total counts. (↓ leakage of system; bursting pressure decrease is lower)[257].

Figure 3.19 Correlation of average AE acceleration amplitude during proof test with failure pressure of glass/epoxy rocket motor cases [122].

Figure 3.20 Correlation of AE counts at low load level with failure level of graphite/epoxy part made from tape [198].

Figure 3.21	Differences in AE counts (during hold cycle at proof level) for acceptable vs. unacceptable composite closures [278].
Figure 3.22	AE signature differences (during proof testing of Kevlar 49/epoxy pressure vessels) versus matrix content [152].
Figure 3.23	Correlation of pressure of early AE peak and failure level for filament-wound glass/epoxy pressure vessels [201].

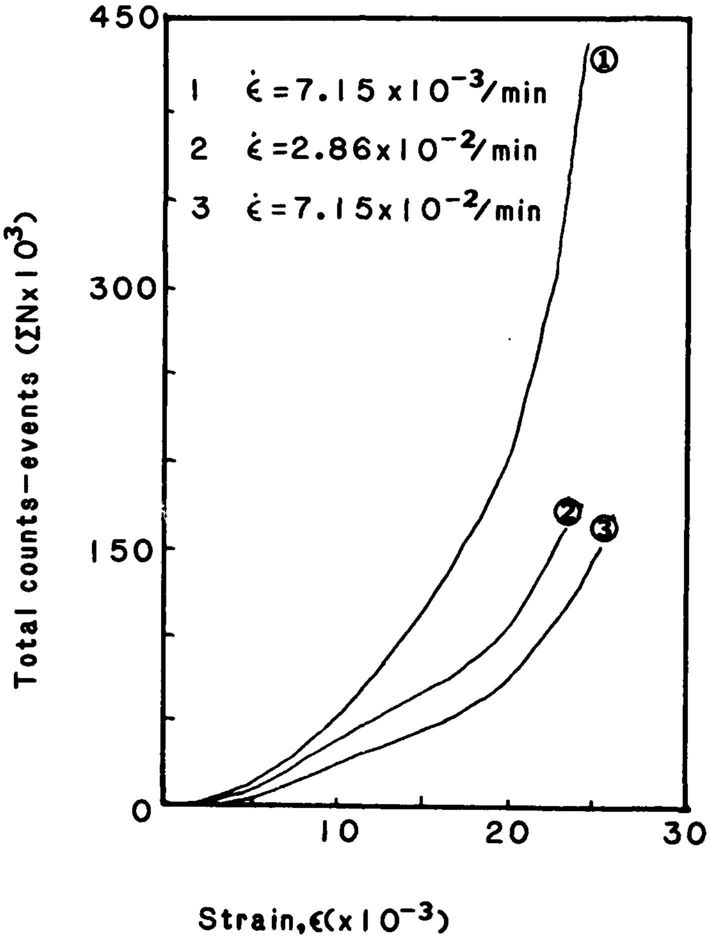
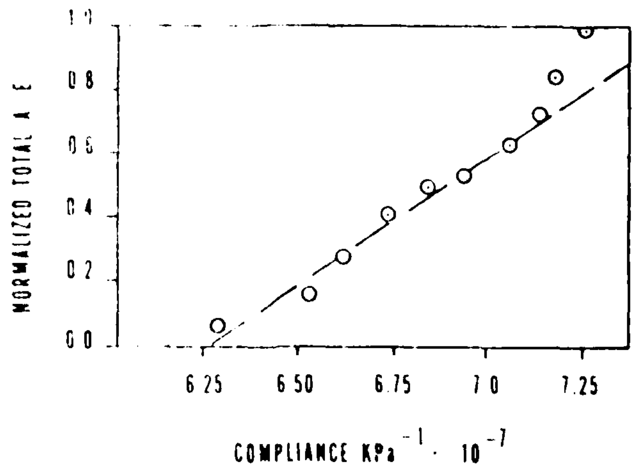

450
300
150
0
10
20
30
1 $\dot{\epsilon}$=7.15 x 10^{-3}/min
2 $\dot{\epsilon}$=2.86x10^{-2}/min
3 $\dot{\epsilon}$=7.15x10^{-2}/min
①
②
③
Total counts-events (ΣN x 10^3)
Strain, ε(x 10^{-3})

Fig. 3.1



1.0
0.8
0.6
0.4
0.2
0.0
NORMALIZED TOTAL A.E.
6.25
6.50
6.75
7.0
7.25
COMPLIANCE KPa^{-1} · 10^{-7}

Fig. 3.2

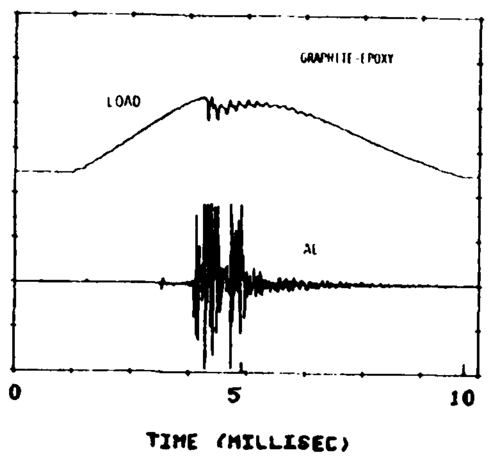


Fig. 3.3

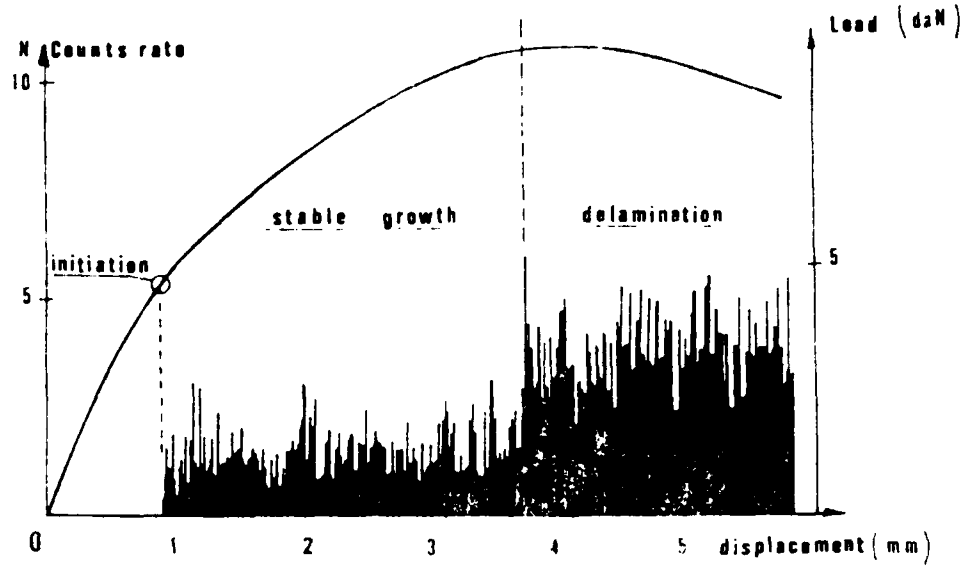

N Counts rate
10
5
0
Load (daN)
5
initiation
stable growth
delamination
1
2
3
4
5
displacement (mm)

Fig. 3.4

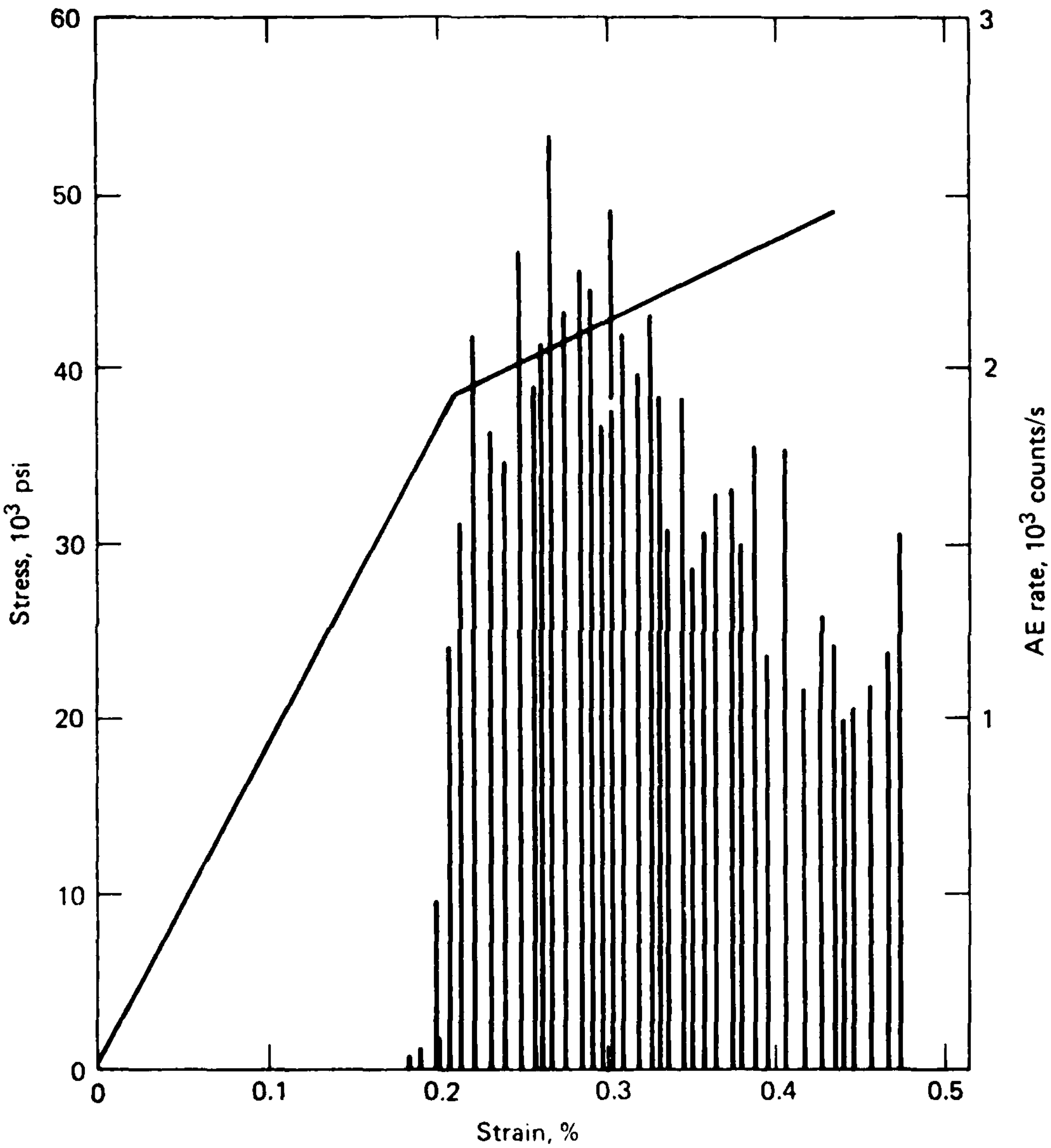

60
50
40
30
20
10
0
Stress, 10^3 psi
3
2
1
AE rate, 10^3 counts/s
0
0.1
0.2
0.3
0.4
0.5
Strain, %

Fig. 3.5

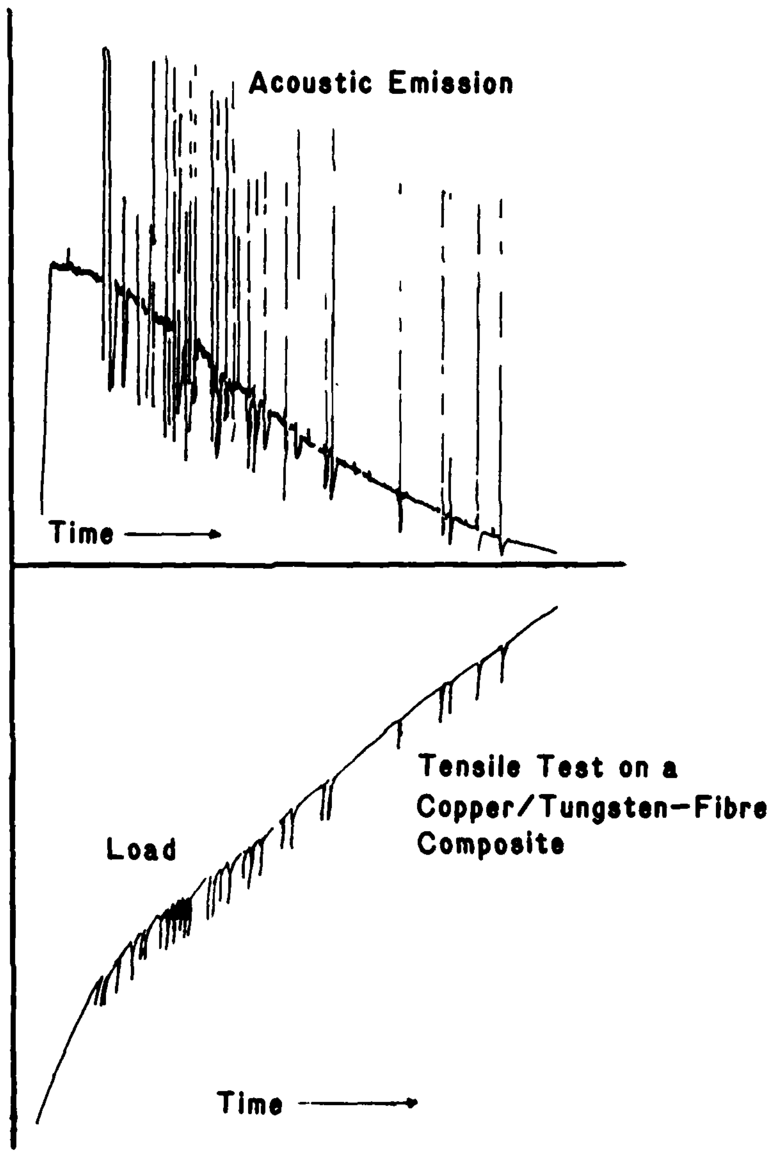

Acoustic Emission
Time
Tensile Test on a
Copper/Tungsten-Fibre
Composite
Load
Time

Fig. 3.6

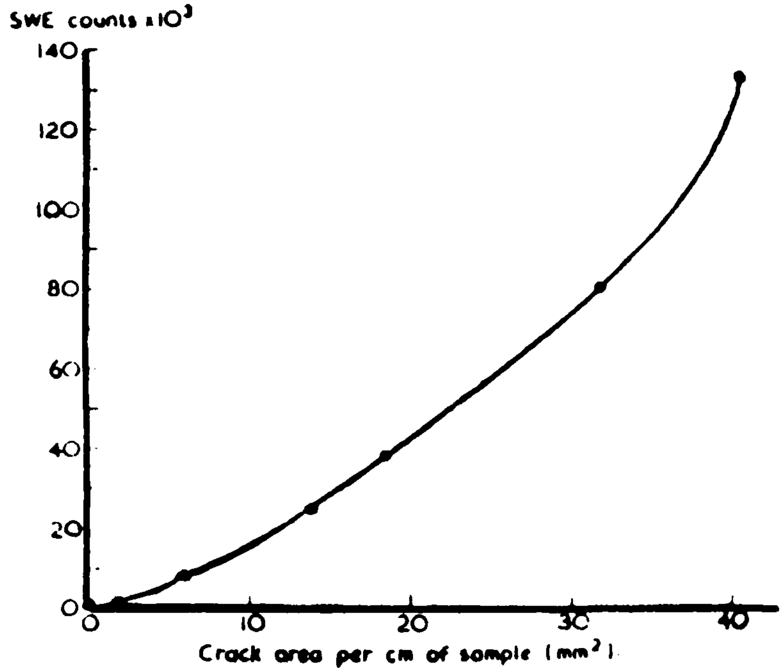

SWE counts x10³
140
120
100
80
60
40
20
0
0
10
20
30
40
Crack area per cm of sample (mm²)

Fig. 3.7

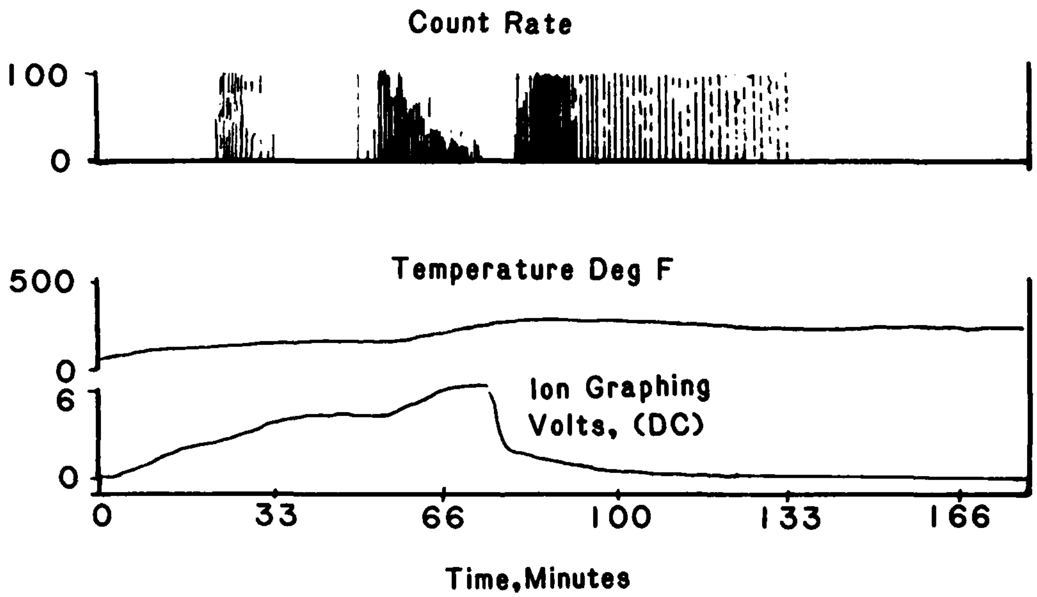
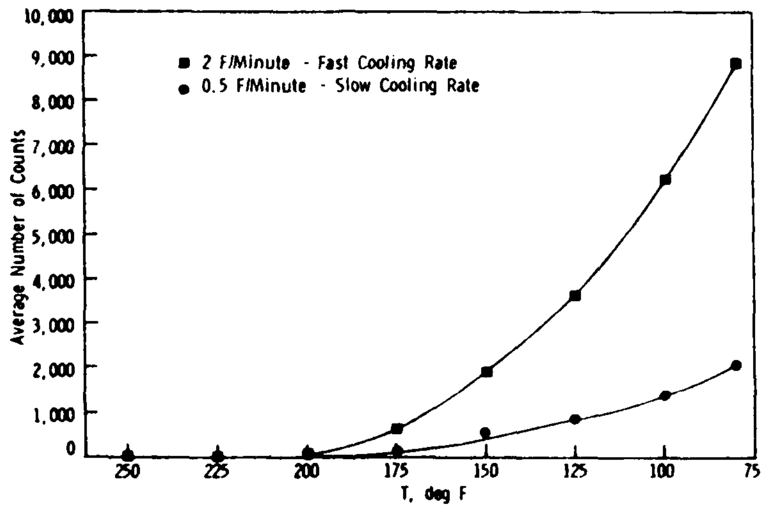

Count Rate
100
0
Temperature Deg F
500
0
6
Ion Graphing
Volts, (DC)
0
0
33
66
100
133
166
Time,Minutes

Fig. 3.8



2 F/Minute - Fast Cooling Rate
0.5 F/Minute - Slow Cooling Rate
Average Number of Counts
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
250
225
200
175
150
125
100
75
T, deg F

Fig. 3.9

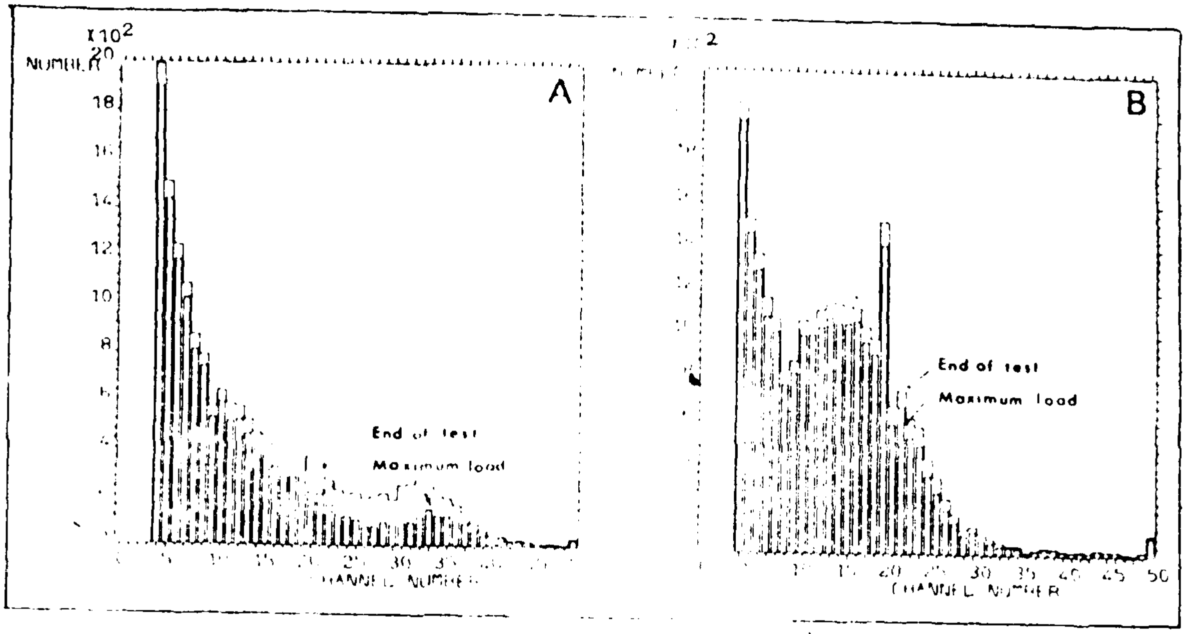


Fig. 3.10

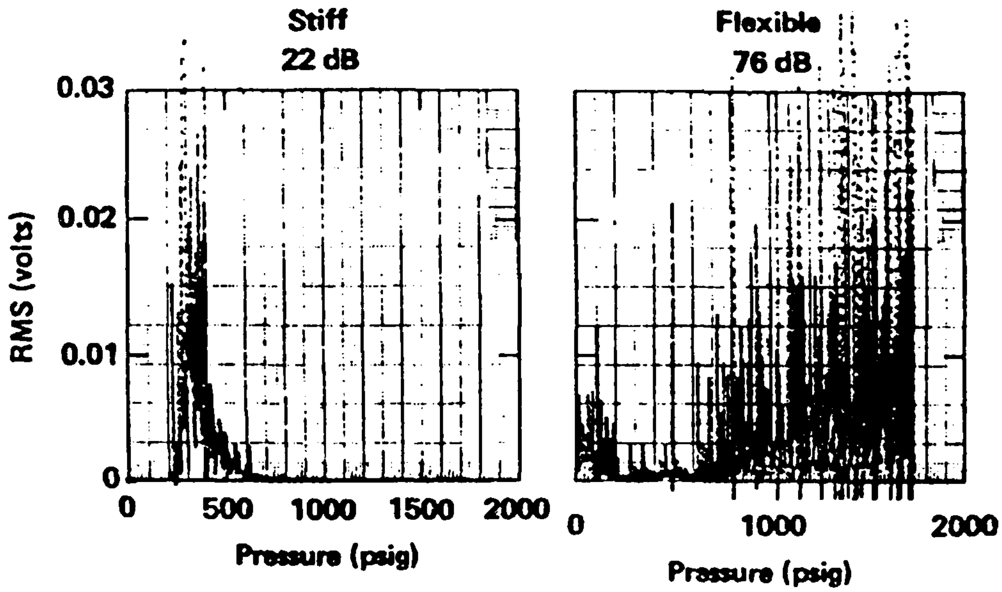

Stiff
22 dB
Flexible
76 dB
0.03
0.02
0.01
0
RMS (volts)
0
500
1000
1500
2000
Pressure (psig)
0
1000
2000
Pressure (psig)

Fig. 3.11

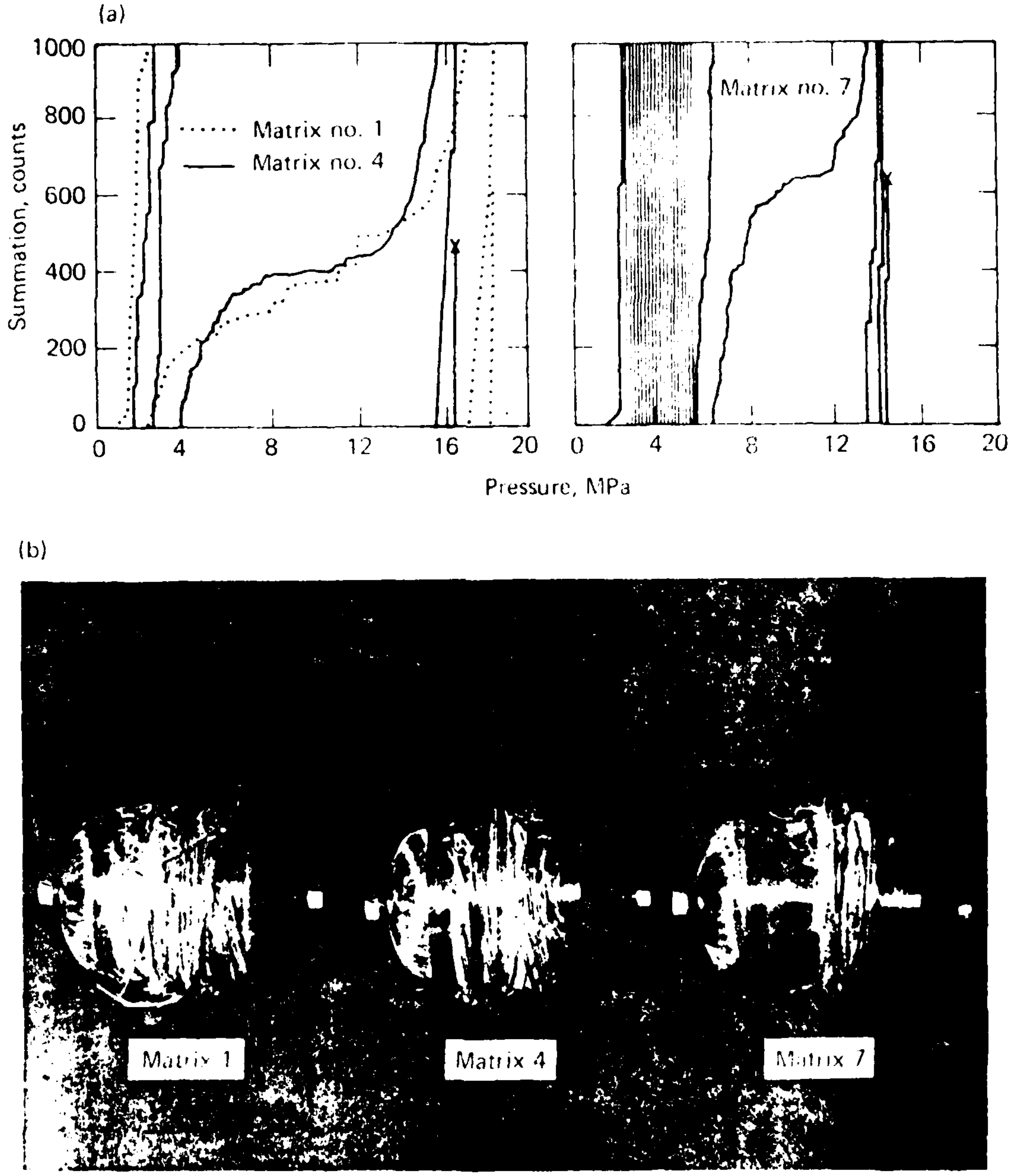
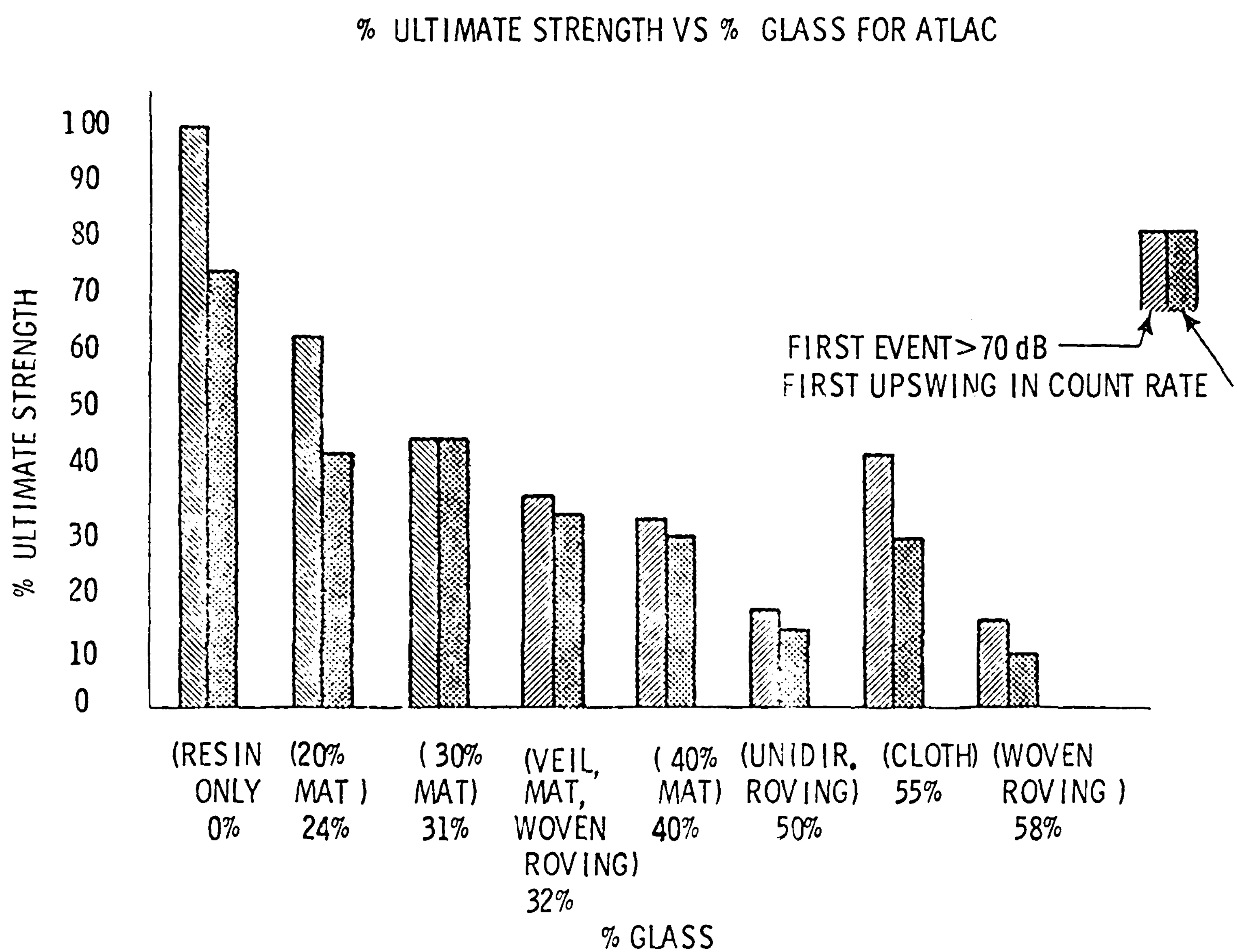
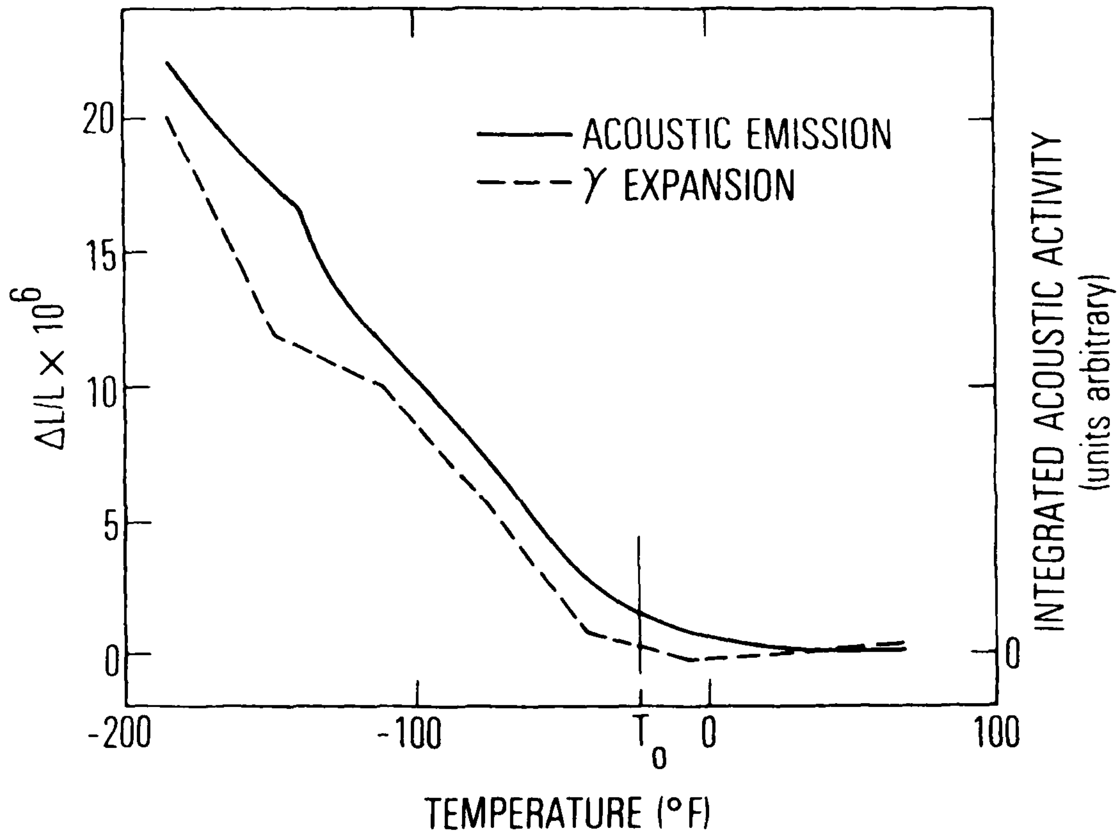

(a)
Summation, counts
1000
800
600
400
200
0
Matrix no. 1
Matrix no. 4
Matrix no. 7
0
4
8
12
16
20
Pressure, MPa
(b)
Matrix 1
Matrix 4
Matrix 7

Fig. 3.12



% ULTIMATE STRENGTH VS % GLASS FOR ATLAC
% ULTIMATE STRENGTH
100
90
80
70
60
50
40
30
20
10
0
FIRST EVENT>70 dB
FIRST UPSWING IN COUNT RATE
(RESIN ONLY 0%
(20% MAT) 24%
(30% MAT) 31%
(VEIL, MAT, WOVEN ROVING) 32%
(40% MAT) 40%
(UNIDIR. ROVING) 50%
(CLOTH) 55%
(WOVEN ROVING) 58%
% GLASS

Fig. 3.13



ACOUSTIC EMISSION
γ EXPANSION
ΔL/L × 10^6
INTEGRATED ACOUSTIC ACTIVITY (units arbitrary)
20
15
10
5
0
0
-200
-100
T0
0
100
TEMPERATURE (°F)

Fig. 3.14

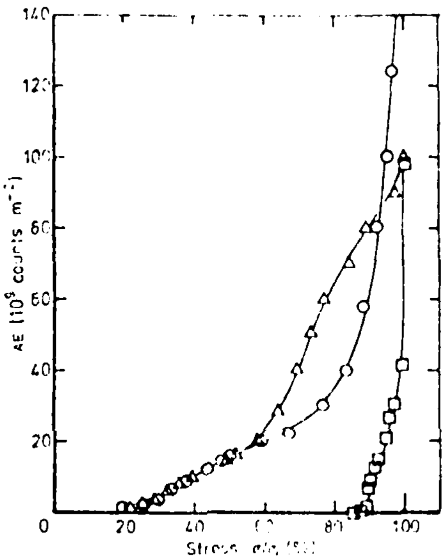
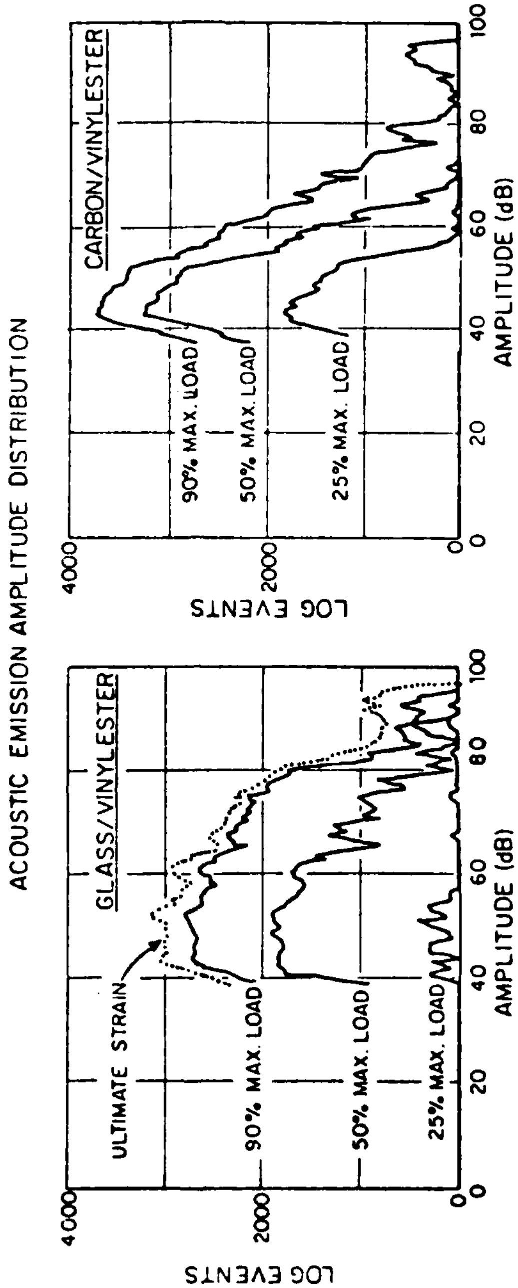


Fig. 3.15



ACOUSTIC EMISSION AMPLITUDE DISTRIBUTION
GLASS/VINYLESTER
ULTIMATE STRAIN
90% MAX. LOAD
50% MAX. LOAD
25% MAX. LOAD
LOG EVENTS
4000
2000
0
AMPLITUDE (dB)
0
20
40
60
80
100
CARBON/VINYLESTER
90% MAX. LOAD
50% MAX. LOAD
25% MAX. LOAD
LOG EVENTS
4000
2000
0
AMPLITUDE (dB)
0
20
40
60
80
100

Fig. 3.16

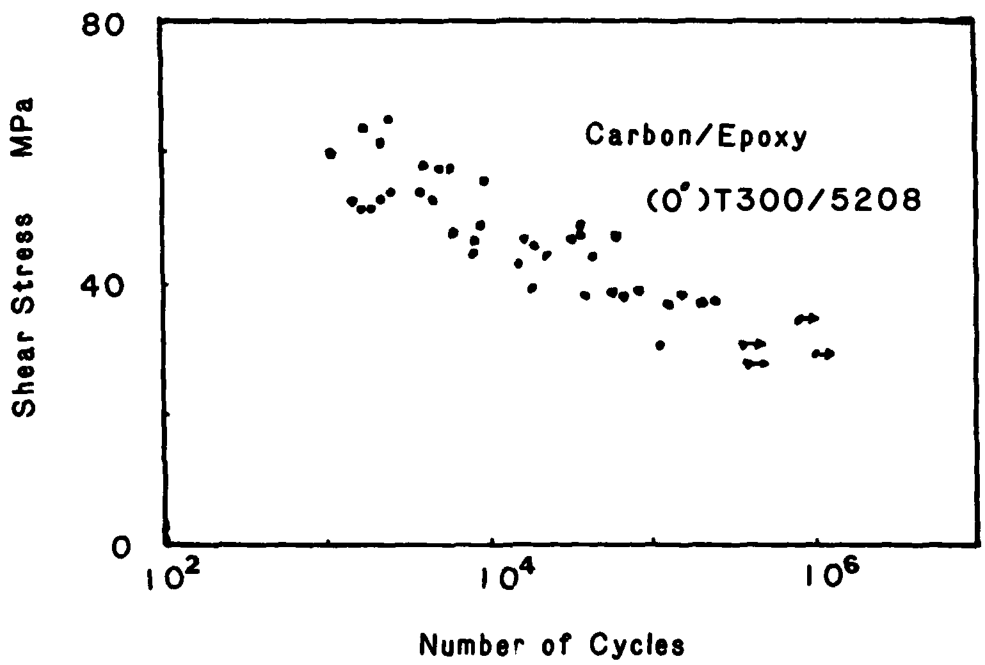
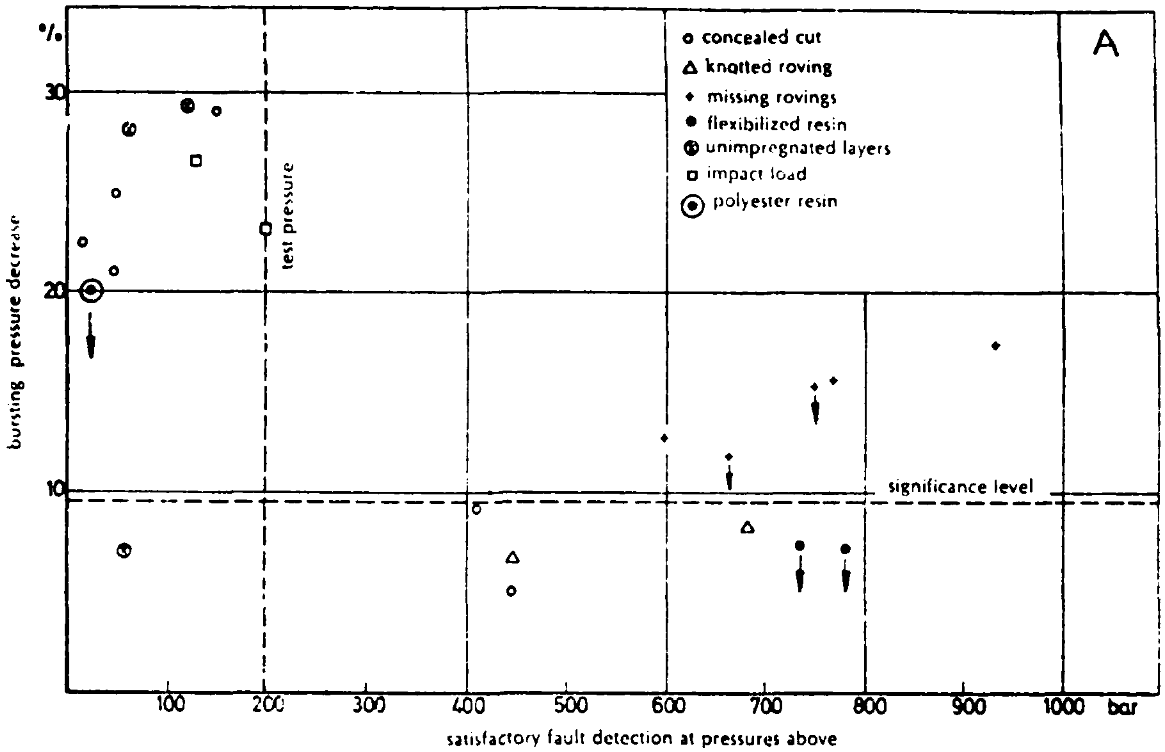

80
40
0
Shear Stress MPa
Carbon/Epoxy
(0°)T300/5208
10^2
10^4
10^6
Number of Cycles

Fig. 3.17


A
%
30
20
10
bursting pressure decrease
test pressure
concealed cut
knotted roving
missing rovings
flexibilized resin
unimpregnated layers
impact load
polyester resin
significance level
100 200 300 400 500 600 700 800 900 1000 bar
satisfactory fault detection at pressures above

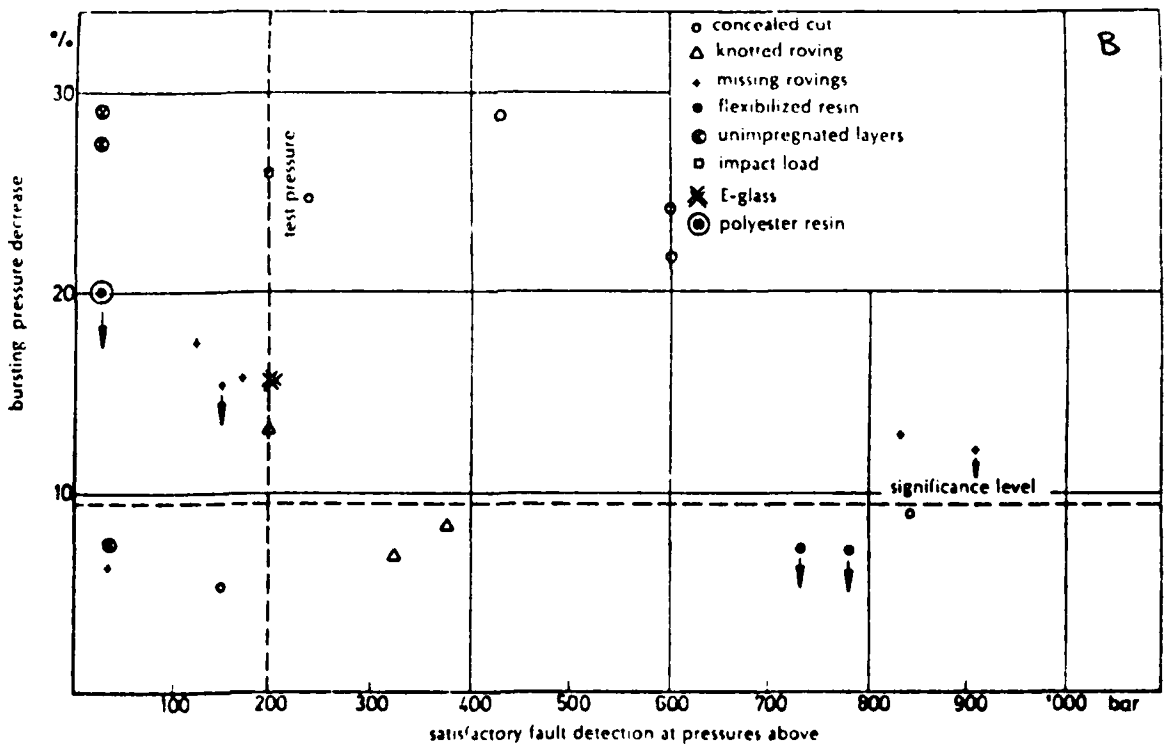

B
%
30
20
10
bursting pressure decrease
test pressure
concealed cut
knotted roving
missing rovings
flexibilized resin
unimpregnated layers
impact load
E-glass
polyester resin
significance level
100 200 300 400 500 600 700 800 900 1000 bar
satisfactory fault detection at pressures above

Fig. 3.18

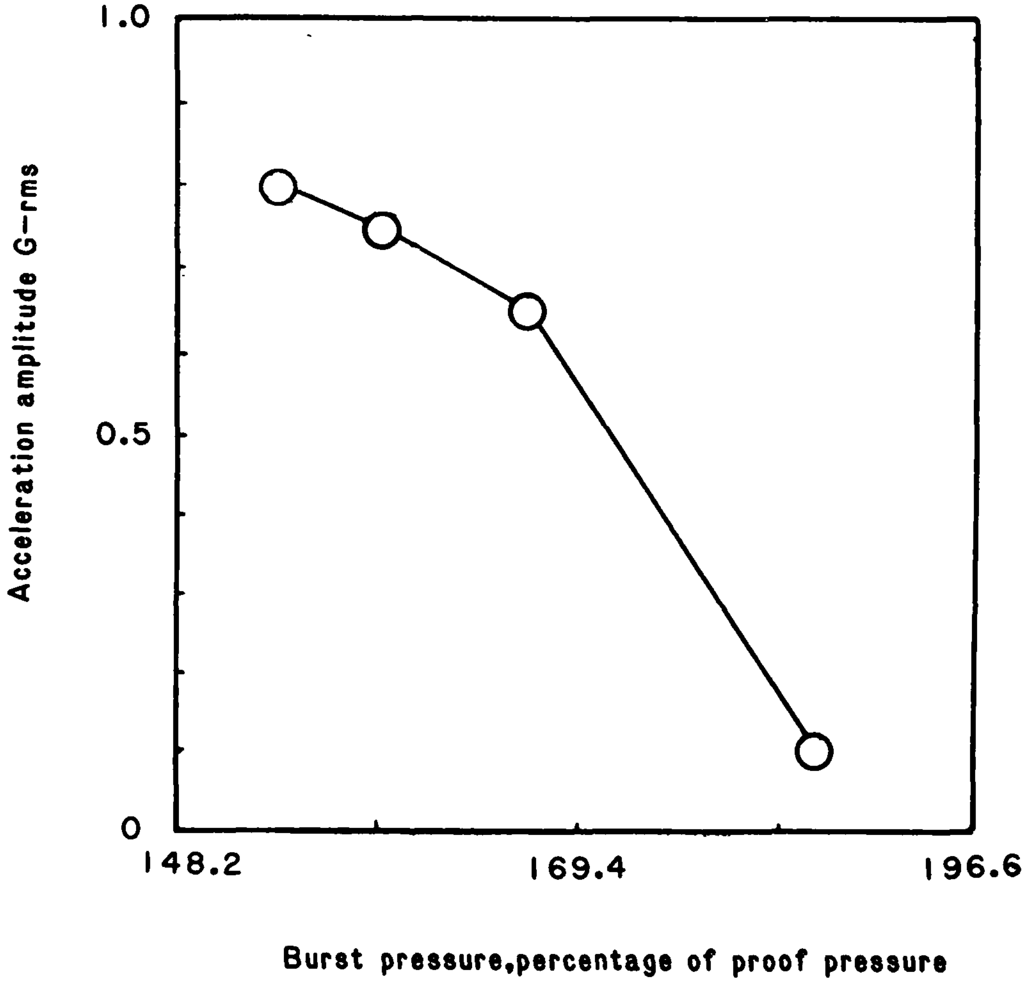
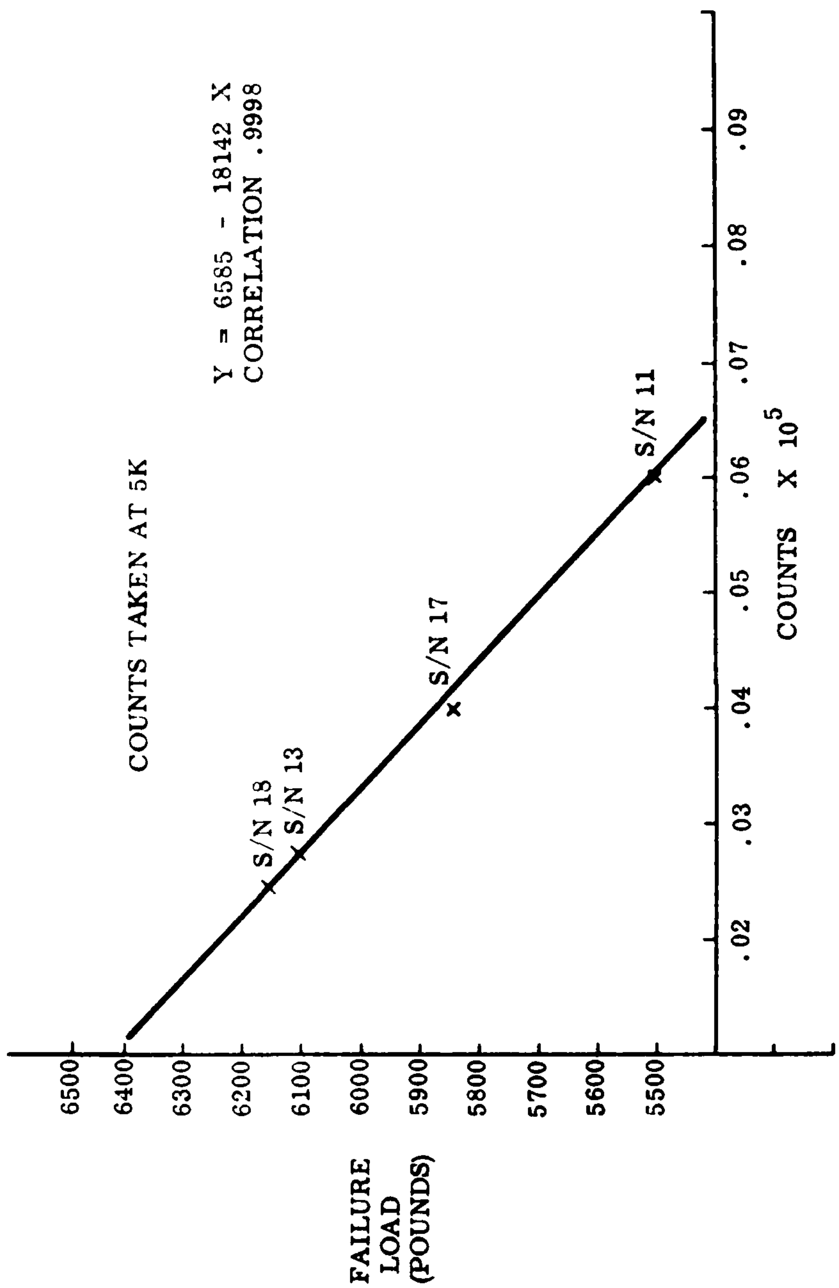
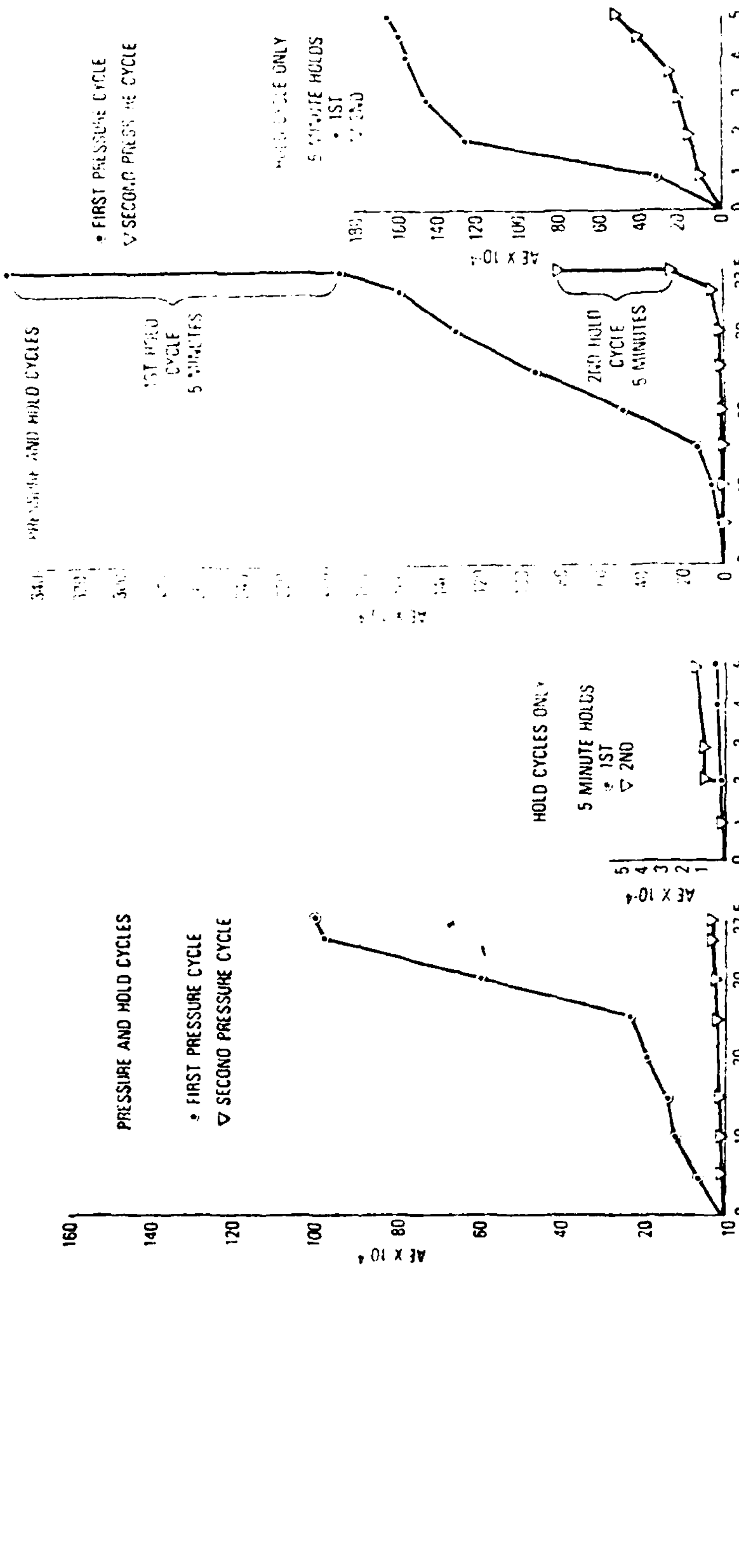

1.0
0.5
0
Acceleration amplitude G-rms
148.2
169.4
196.6
Burst pressure,percentage of proof pressure

Fig. 3.19



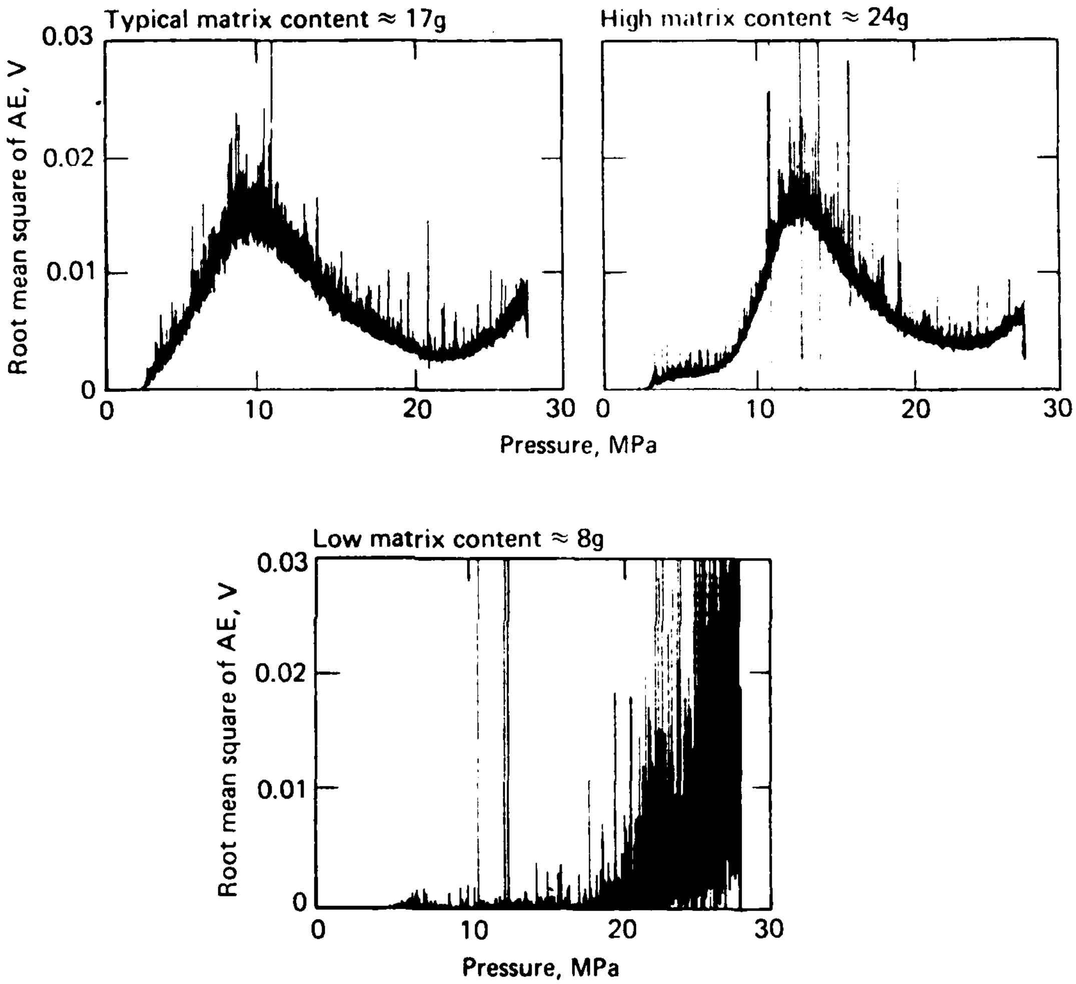
Y = 6585 - 18142 X
CORRELATION .9998
COUNTS TAKEN AT 5K
S/N 18
S/N 13
S/N 17
S/N 11
FAILURE
LOAD
(POUNDS)
6500
6400
6300
6200
6100
6000
5900
5800
5700
5600
5500
.02
.03
.04
.05
.06
.07
.08
.09
COUNTS X 10^5

Fig. 3.20



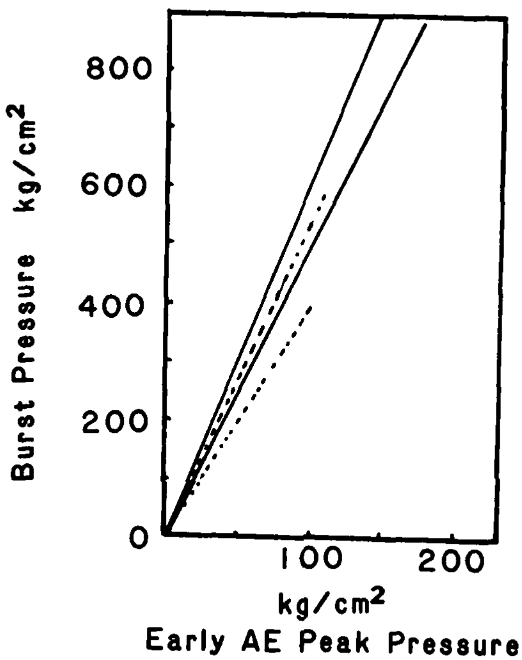
PRESSURE AND HOLD CYCLES
FIRST PRESSURE CYCLE
SECOND PRESSURE CYCLE
AE X 10⁴
PSI
HOLD CYCLES ONLY
5 MINUTE HOLDS
1ST
2ND
MINUTES
2ND HOLD CYCLE 5 MINUTES

Fig. 3.21



Typical matrix content ≈ 17g
High matrix content ≈ 24g
Low matrix content ≈ 8g
Root mean square of AE, V
0.03
0.02
0.01
0
0
10
20
30
Pressure, MPa

Fig. 3.22



800
600
400
200
0
Burst Pressure kg/cm²
100
200
kg/cm²
Early AE Peak Pressure

Fig. 3.23

Part 4 - Review of Progress in Research on AE from Composites

Introduction

The purpose of this part of this report is to review progress where the technology of AE from composites is still in development. To effectively organize this part of the report, the technology was broken down into several key areas. In each area significant results, ideas, or conclusions will be referenced. As with Part 3 these key results will not be summarized in detail. Instead the reader is referred to the original reports. Following the references to significant results, this author will, where it is appropriate, briefly discuss the progress in that area as well as give some suggestions concerning future work. Also, where appropriate, a discussion will be made of what the pay off will be if certain progress is made.

AE Instrumentation for Composites

In many cases, during testing of composites the rate of AE events is very high. This can result in AE equipment, which characterizes each AE event, being unable to keep up with the event rate. Guild *et al.* (1980) and Phillips (1981) demonstrated that an AE amplitude distribution system could not keep up with a certain event rate, while a simple threshold counting system was still able to keep up with the event rate. They also stated that the AE amplitude distribution system was slower in the differential mode than in the cummulative mode. These results indicate the need for the development of AE instrumentation for composites which can handle very high data rates.

Several special measurements have been developed or proposed for use with composites. Hamstad and Patterson (1977) showed that a certain true root mean square (rms) meter could be used to measure the energy in AE bursts in composites when these bursts were separated by 1

to 2.5 seconds. They showed there were large energy changes in real AE events (from composites) which had only small changes in peak amplitude (see figure 4.1). Laroche and Bunsell (1980) developed a logarithmic period meter which gave values of the log time for a fixed number of AE events. They found this information was useful in the study of load history effects on damage accumulation in composites. Hamstad (1981) described the use of a clipping device which limits the maximum amplitude of AE events. The purpose of this clipper was to allow the use of a true rms meter to measure the energy rate of low level continuous AE which had high amplitude burst type AE superimposed on it. Sundaresan et al. (1982) reported use of a weighted, four-threshold counting technique to obtain a better measure of cummulative AE energy. They selected this approach as a means to overcome the wide dynamic range of AE events in composites. They had observed that simple threshold counting of AE signals did not show the large proportion of AE energy which was released near failure. Graham (1978, 1979) reports the use of the multiparameter analyzer (MPA) to characterize AE events from composites. This instrument can characterize each AE event by means of 23 separate parameters and can operate at up to 3000 events/sec.

In this writer's opinion, the direction in the future for AE instrumentation for composites will be determined from studies where each AE event has been digitized. After digitization sophisticated techniques of characterization and analysis can be applied using a computer. Since AE event rates and storage of data are currently limited for composite AE testing, the digitization of events approach is only currently applicable in research devoted to determining what

characteristics of the AE signals can be best used to determine such things as source identification, source location, and criticalness of source. When these characteristics are better understood, then AE instrumentation can be designed to measure these characteristics at high data rates for use in applications.

On AE Testing With Composites

A key question with AE testing of composites concerns the development of test techniques such that extraneous noise sources are controlled or eliminated. Thus considerable effort has been expended towards this end. For field testing of tanks, Fowler et al. (1979) listed several potential noise sources: 1) agitators, 2) valve movement, 3) traffic over cables, 4) steam traps, 5) supports on a sand base, 6) wind causing cable slap, and 7) entrapped gas bubbles. Mitchell (1981) also lists extraneous noise sources which can be present in field testing as well as potential solutions to these problems.

For laboratory testing, Brown (1975) observed that there is less extraneous noise for a three-point bend test than a tension test for a composite. Fry (1977) pointed out the need for rubber sleeves for the loading and reaction noises in the three-point bend test. Sherer and Ashley (1981) used electricians PVC tape at these locations to reduce extraneous noise. They used a pulser on the test fixture to evaluate the isolation which this technique provided.

A large number of investigators have made some efforts to evaluate and control the potential sources of extraneous AE from tensile tests on composites. Before listing some of the suppression techniques as well as results of noise studies, there are three facts which should be pointed out. First, the effectiveness of noise suppression techniques

depends on the sensitivity of the AE system with respect to the AE test set-up. Such variables as system gain, threshold, and bandpass as well as sensor type, location, and couplant and also the test fixturing and specimen size and type, all affect the sensitivity. Thus the approach that controls extraneous noise for one experimenter may not work for another. Second, not all workers have done a sufficiently detailed study in this area. Thus a reported technique to control extraneous AE may not in fact do so. Third, what seems to be needed are standards for how extraneous noises should be evaluated for particular tests. These standards could include tests which use a pulser or other AE simulator to measure the attenuation characteristics of certain noise isolators which have been used.

Two experimenters replaced the composite coupon samples with a pure (noise free) matrix sample to check for extraneous noises with the tab type tensile test. Mazzio et al. (1973) used this approach to help to evaluate the use of flat, smooth, air operated grips. Fuwa et al. (1976) used this approach to evaluate noise from tab adhesives and determined that the shear in the adhesives must be kept below a certain value.

A number of experimenters have replaced the standard fiberglass tabs with metal tabs in an attempt to reduce noise from the interaction of the grips and tabs. In this case, Fowler and Gray (1979) bonded aluminum tabs to a simulated specimen of stainless steel to check for adhesive induced extraneous AE. Bunsell et al. (1974) and Henneke and Herring (1925) used a similar approach in bonding aluminum tabs to an aluminum coupon sample. Eikelboom (1979) stated the need to check for creep noise originating in the tab adhesive.

Mullin et al. (1972) listed the sources of extraneous noise with tab-type grips for composite coupon samples: 1) metal to metal contact, 2) wedge type grips, and 3) the adhesive bond. Their approach to solving these problems was to use pin loaded grips with steel tabs. They coated the pins with rubber and used double holes in the tabs so they could preload part of the adhesive bond and tab before the tensile test was done.

Two experimenters used the loss of the Kaiser effect to demonstrate extraneous noise difficulties. Dingwall and Mead (1974) showed, compared to the normal second cycle AE, that when after initial loading the tabs were cut off and replaced with new tabs, the Kaiser effect was violated. Hamstad (1981) showed by removal and reinstallation of the sample from the grips that the Kaiser effect was violated due to wedge type serrated jaws digging into the tabs at new locations (see figure 4.2). This demonstrated that a substantial source of extraneous AE was present in the first load cycle.

In summary, concerning tensile testing, this author believes that more work is necessary to provide a knowledgeable solution to extraneous noise. The test procedures outlined in Part 2 should be used and standards as mentioned above should also be implemented. In addition, variables such as the effect of the ratio of modulus of the tab material to the composite modulus needs to be investigated as a function of adhesive type and thickness. The final solution is not just elimination of extraneous AE, but it must not cause problems due to changes in the stresses near the tab ends which could be caused by using tab materials with different moduli.

Fatigue testing with AE monitoring brings new noise problems. Ryder and Wadin (1979) take a typical approach in using guard sensors. This approach places a sensor between the data sensor and the extraneous noise sources. They found a reduction of 30 dB in fixture, grip, and test machine noise. Weyhreter and Horak (1978) used a more extensive approach to extraneous fatigue noise. They also used the guard sensor concept (calling it a master-slave combination of sensors). In addition, they used: 1) Coincidence - that is, only accepting AE events whose arrival times indicate that the event originated between data sensors; and 2) Waveform requirements - that is, only accepting AE events with rise times of certain values. The three approaches outlined here have difficulties when AE event rates are high or if it is not possible to locate guard sensors away from the specimen gage section (e.g., guard sensors placed on the composite near the tabs will effectively also eliminate AE events of interest).

Fatigue testing has also been observed to cause another source of extraneous AE. Williams and Reifsnider (1979) observed AE noise from rubbing or scraping of delaminated surfaces during fatigue testing. Rollins (1971) observed fretting noise due to shear cracks running parallel to the fibers during fatigue testing. This result was verified by observing a reduction in the noise when the crack surfaces were lubricated with oil or water. For rubbing type noises, a technique which keeps track of where, in each fatigue cycle, the AE occurred is useful to separate rubbing AE from that generated by new damage.

Specimen design or orientation of the test specimen seems to have been used to advantage in composite testing with AE monitoring. Graham (1979) used a small four-point bend specimen with only a very short

reduced section with a triangular shape. This approach minimized differences in the path from the AE source location to the sensor. Hence the specimen variables were not as large as they would be for events originating at random locations over a relatively large specimen. This type of approach could lead to a clearer distinction between AE events of different source types. Another similar approach has been used by Schwalbe (1973) and Rotem and Altus (1979). In this approach unidirectional samples have been fabricated into specimens similar to compact fracture specimens but the orientations of the specimens have been chosen to result in various fracture paths with respect to the fibers.

To close this section, three references to effects with AE sensors will be noted. Hutton (1975) found that "hot glue" material used to bond sensors to a composite part became partially unbonded as the specimen was loaded. This resulted in some extraneous AE being generated. The high elongations which occur in testing composite structures compared to metal structures may mean that sensor attachment techniques which work on metals may have to be changed. Lark and Moorhead (1978) noted that mounting AE sensors on the aluminum bosses of a composite pressure vessel resulted in less spread in data than that from sensors mounted on the vessel surface. This result was evidently due to attenuation effects not being as large since placement of the sensor with respect to the failure region did not vary as much from part to part. Sims and Gladman (1979) investigated effects of sensor type and sensor location on test results. They also examined effects of sensitivity and specimen variables such as the width of the gage section on the AE results.

Wave Propagation and Attenuation In Composites

A number of researchers have measured velocities of propagation in composites. Typical values are as follows: Schwalbe (1978) stated wave speeds in the axial direction in 60° glass tubes were about 2.4×10^3 m/sec; Bailey et al. (1978) observed in 62% fiber volume graphite/epoxy angle plys the velocity was about 6×10^3 m/sec in the 0° direction and about 3×10^3 m/sec in the 90° direction; Green et al. (1963) measured velocities in E-glass and S-glass filament wound rocket motor cases ranging from 2.7×10^3 m/sec to 3.3×10^3 m/sec for shear and 3.0 to 5.2×10^3 m/sec compressional waves. Also there was no significnt change in the velocities up to about 50% of the burst strength; Hamstad and Chiao (1976) measured wave speeds in a Kevlar/epoxy laminate at about 2,330 m/sec at 5 Mhz and 1,180 m/sec at 2.25 Mhz; Rathbun et al. (1971) recorded wave speeds of $1.5\text{-}1.7 \times 10^5$ m/sec on filament wound glass/epoxy pressure vessels; Eselun et al. (1979) recorded a sound speed of about 914 m/sec in graphite/epoxy, which they said was about the same speed as in pure epoxy.

As, can clearly be seen above, the velocity of propagation varies greatly in composites even when the same material is involved. It also varies with direction of propagation as well. Hence, it is almost always necessary to measure the velocity if it is going to be used for source location purposes. It is also clear that due to the variation of velocity with direction of propagation, it may be difficult to calculate source locations based on velocities. This result will be discussed in more detail in the section on source location.

Attenuation, or more properly, signal propagation losses have been studied by many researchers. But given the number of variables

which effect signal propagation losses, in this author's opinion it has not been sufficiently studied. The table below lists some references and results under the indicated conditions.

Authors	Results
Pollock and Cook (1976)	In glass/plastic losses were much greater for 100 kHz high pass than 10 kHz high pass using a pulser as a simulated source (see figure 4.3).
Graham (1977)	Graphite/epoxy is a dispersive medium at <600 kHz and the level of dispersion depends on the direction of propagation vs. the fiber direction.
Graham (1977)	Attenuation is both frequency and directionally dependent in about the same fashion for both one- and two-dimensional samples.
Hamstad (1980)	Due to signal propagation losses on a 4.5 inch diameter spherical Kevlar/epoxy pressure vessel, with a band pass of 200-300 kHz it was not possible to observe the AE from

	a locally growing flaw which was clearly observed with a 5-25 kHz bandpass (see figure 4.4).
Hamstad (1980)	Proposed that signal propagation losses may vary depending on the AE source mechanism in composites.
Hutton (1975)	Measured attenuation in nylon/-polyurethane for real AE signals. For a 20 kHz high pass filter the average value was 7.8 dB/ft and for 5 kHz high pass the average value was 3.6 dB/ft.
Crump and Droge (1979)	Studied attenuation in several glass/plastics using a 100-300 kHz bandpass. They obtained similar results using both a pulser and a lead-break technique. The value was about 24 dB/ft.
Hamstad and Patterson (1977)	In a sphere with a 5-30 kHz band-pass the energy from lead breaks propagated according to $\mathrm{Sin}^{1/2}\theta$, where θ is the angle propagated through.

Hamstad & Chaio (1976)	Compared metal with composite pressure vessels for signal propagation losses by counts per glass-capillary break. For a cylinder the counts per break varied by a factor of 10 for the metal and 55 for the composite. Similar figures for the sphere were 3.4 and 17 for a 100-300 kHz bandpass.

The above results indicate again a diversity of results for signal progation losses. One technique (besides lowering of the frequency bandpass) which has been used successfully is an immersion sensor. This was first developed by Dean and Kerridge (1976). They found that the immersion sensor was about 20 dB less sensitive than a surface mounted sensor on a composite pressure vessel, but it gave much more uniform coverage. Hamstad (1979) made a direct comparison for lead breaks on an 8 inch diameter Kevlar/epoxy sphere and found that with a 5-50 kHz bandpass, the energy from lead breaks varied by a factor of 1.7 for the immersion sensor vs. 49 for the surface mounted sensor. Later, Hamstad (1981) showed that the immersion sensor could be conveniently replaced by a waveguide which penetrated the pressure vessel (see figure 4.5).

Another aspect which relates both to attenuation and AE event duration has been seen in filament wound pressure vessels. Dean and Kerridge (1976) observed that if the vessel is water-filled a consider-

able share of the AE signal comes to the AE sensor by way of propagation through the water. They also observed that changes in the depth of water could cause considerable differences since the AE signal bounces around the pressure vessel and the fluid several times before it dissipates away. Hamstad (1979) clearly showed that the duration of the AE event is due to this bouncing around the part. Hamstad and Patterson (1977) indicated that attenuation could lead to two types of AE events: 1) Local events of short duration ($\approx$ 0.5 ms) with an AE time domain similar to that from a lead break on the face of a sensor, with these local events only sensed at one sensor; 2) In contrast, other events had long durations (5-7 ms) and were sensed by several sensors on the part.

In summary, wave propagation effects deserve more consideration by experimenters. It would be very desirable for more experiments to be carried out with multiple sensors at different locations to better characterize the changes in AE events due to propagation. Use of transient recorders would be ideal for this. Also useful would be computer based AE systems which could characterize each event at each sensor so that comparisons could be made of parameters such as rise time, peak amplitude, duration, and energy. This information would provide a better basis to distinguish propagation effects on AE signals from changes in AE source mechanism.

Sensors For Composites and Calibration For AE Tests

We will first discuss several sensor concepts for composites and then some results of sensor experiments. Golis et al. (1973) described the concept of a wheel mounted sensor for use in continuous inspection of composite pipe at the end of the manufacturing line.

Eselun et al. (1979) described the advantages of an optical AE sensor for composites. Its low frequency sensitivity meant they could listen to the AE and by ear distinguish cracking in the composite from other background noise. They also saw greater sensitivity by operating at low frequency since they stated the displacements for a given crack are larger at low frequency. Stiffler and Henneke (1981) describe the advantages of a polyvinylidene floride sensor for composites as being: 1) light weight, 2) flexible so it can fit a curvature, 3) inexpensive, 4) wide band, 5) flat response, 6) and it can be cut to the size and shape needed. Its disadvantage was that it was at least 40 dB less sensitive than commercially used AE sensors. Another sensor which may be useful for composites but which has not yet been reported in the literature is the sensor that has been developed by workers at the National Bureau of Standards (NBS). This piezioelectric sensor which is modeled to have the same response (i.e., to vertical displacements) as the capacitive sensor used at NBS in the calibration of sensors, may be useful for AE source identification studies because of its flat response.

Hamstad and Patterson [1977] and Hamstad [1979] in two papers made a number of observations about AE sensors particularly at the low frequencies which were used for monitoring composites. For example, they found that machining away part of the epoxy shoe on a particular commercial sensor to leave a button in the center increased the sensitivity by a factor of 2.5 times. In a more general study, it was found for a 5-100 kHz bandpass the AE sensor sensitivity increases if the button face sensor is used with a high viscosity couplant or if a low viscosity couplant is used with a standard flat face sensor. In

studies with lead breaks they found that with a 5-30 kHz bandpass that couplant volume and thickness did not change the AE time or spectral domains, while a mere change to another AE sensor of the same type did change the spectral sensitivity.

Relatively little work has appeared in the literature (of AE testing of composites) dealing with calibration of the AE tests. Hamstad and Patterson (1977) and Hamstad (1978, 1981) show two separate fixtures which were developed to provide an in situ calibration of the AE proof test of a composite pressure vessel and a composite dome using a lead break on the surface of the composite. The load at which the lead fails is measured to assure a good calibration signal. In order to make these calibrations repeatable special fixturing was needed both to hold the test part as well as the AE sensor and the lead breaker (see figure 4.6). In a related area, Hutton (1975) reports a vibration marking tool as a calibration source which gives frequencies in the 5-30 kHz range.

In summary, too little effort has been extended in this important area for applications of AE testing. The result is too little understanding of the variables which can effect the repeatability of an AE test. This leads to inconsistencies in AE data which cannot be explained due to changes in test specimens or structures.

Source or Area Location In Composites

In the area of source location in composites, differing results have been reported in the literature. In this report, we will first note some references with some brief comments where source location techniques were used. Next, we will cover the difficulties that have

been observed with respect to source location in composites and indicate some approaches to their solution.

Reference	Comments
Green et al. (1963)	Used triangulation on AE events to determine failure location which was confirmed by high speed photography.
Rathbun et al. (1971)	Accomplished linear location on a 3-inch diameter glass/epoxy sphere. Determined most AE events occurred at the poles and verified most fiber breaks were located there by burning off the epoxy and unravelling the fiber.
Kelly et al. (1975)	Used source location to monitor punch loading at one point of a graphite/epoxy face plate of a honeycomb panel.
Hutton (1975)	In nylon/polyurethane used linear location to prove that many AE events originated at the eventual failure site.
Bailey et al. (1979, 1979)	Used AE source location (two dimensional) to locate and see the progression of damage growth during tensile loading of

	graphite/epoxy plates which had been damaged by impact. During this loading few AE events originated outside the impact region.
Ryder and Wadin (1979)	Linear event location histograms showed some correlation with a delamination region which was observed visually.

On the subject of difficulties with source location in composites, Dean and Kerridge (1976) observed in composite pressure vessels that water paths could result in confusion for source location systems. In a more detailed study Hamstad (1979) found for liquid filled composite pressure vessels that three significant wave packets were observed. Two packets which propagated in the composite and one which propagated in the liquid. The first arriving composite packet was of low amplitude with high frequency components and the second had higher amplitude and lower frequency components. For a gas filled pressure vessel only composite wave packets were observed. Source location errors could easily arise if the AE system triggered on different packets at different sensors. This result could easily happen in composites due to the high signal propagation losses which are present. Techniques which might be used to improve this situation include filtering to cut down the amplitude of the second packet and then always triggering on the first packet; also design of instrumentation to keep a constant ratio between the threshold level and the peak amplitude of each event might be useful.

Fowler (1977) and Fowler _et al._ (1979) discussed some of the problems of source location in composites. They indicated that due to attenuation it would be necessary to have all four sensors of a location array located within four feet of an AE source to locate it. This would result in the need for very large numbers of sensors for large structures. They also suggested that, due to high AE event rates in composites, multiple events in the same region at the same time increment would cause confusion for the source location system since the array could not distinguish which events came from which source. The problem of different velocities in different directions was also listed as a problem. Because of these problems, Conlisk and Fowler (1977) had advocated the use of an area location technique. In this technique the high attenuation is used so that AE events only reach one sensor before they attenuate below the sensitivity of the AE system. Thus, sensors with high AE activity indicate regions or areas whose critical flaws are located.

Hamstad (1981) suggested a technique to use in research to prove that problems with source location have been overcome:

> The technique involves using Pentel lead breaks at fixed points in a grid drawn on the test specimen. With different lengths of Pentel lead, it should be possible to develop sets of relative time differences, ΔT values, for each point on the grid as well as the peak amplitude range at the various sensors for which these ΔT values are valid. To characterize the amplitude would require transient recording devices for each channel in the source location array or peak amplitude detection for each channel in the array. This approach would

provide the necessary calibration data to prove the AE source locations, determined during the subsequent test, were correct. Thus, we could prove the three main problems of source location in composites, namely, velocity variation in different directions (which leads to incorrect calculations of locations) and the high attenuation and large dynamic range of AE signals in fiber composites (which both lead to incorrect AE arrival times with typical AE equipment used for source location work) had been overcome.

In summary, the successful further development of source location in composites would have two primary benefits. First, we will consider a unique contribution that AE source location can make to resolve the difficulties associated with the NDE of fiber composites. The main difficulty is that often the detected anomalies in a composite test specimen do not cause or control the failure. Because the real controlling flaws are not known, there is a lack of an experimentally based failure-criterion for fiber composites. Since natural, and largely undescribed, flaws often control failure of a fiber composite, the capability of AE to locate the source has the potential to aid in describing the nature of these real flaws and how they grow during increasing load or time. A fruitful use of AE would be to locate a critical flaw prior to a catastrophic failure that so destroys the flawed region that a post-failure study of the region yields little or no information on the description of the original flaw or its growth mechanisms. Then, a careful microstructural examination of the flawed region and a more accurate physical description of the flaw and its growth mechanism could be made. Second, as will become more apparent

later in this part of this report, research results to date indicate that development of source location techniques which are applicable to all composites would substantially enhance the application of AE to NDE of composites. One of the key difficulties at the present time is that stressing a composite leads to the generation of a lot of random AE events which are not related to the flaw growth which will control the failure of the part or structure. With source location it would be possible to focus on the AE events which are occurring at flaws or weak points in the structure and correlate this information such that very reliable predictions of residual strength and/or life could be made. Hence in this author's opinion a high pay off would result from successful completion of research in this area.

Felicity/Kaiser Effects on Composites

In this writer's opinion the fundamental understanding of the Felicity effect has not yet been achieved. It seems that there are a number of variables which may influence the Felicity ratio, but few of these have been studied in detail. Because the AE that is associated with the Felicity effect seems to be closely related to the level of damage or the severity of flaws in a composite structure there will be a large pay off when a full understanding of the physics associated with this effect is understood. With such an understanding it should be possible to tailor proof cycles to maximize the NDE information to be gained.

In this section we will survey some of the progress that has appeared in the literature. We will include comments where it is appropriate. It should be noted that we will use the terms Felicity effect and Felicity ratio (FR) exclusively since these terms are broader and more quantitative than the term Kaiser effect.

One clear application of the Felicity effect seems to be to assess damage or flaws induced in service. The literature does not reveal a lot of research directed towards development of this application. Robinson (1973) reports that after test firing of a composite motor case the FR dropped to about 0.83. Bailey et al. (1978, 1979) reported that impact damage on graphite/epoxy significantly lowers the FR in subsequent tensile testing. They reported results in one test where the ratio dropped to approximately 0.65 after impact damage. Pollock and Cook (1976) and Wadin and Pollock (1977) studied the effect of introducing a flaw in a composite after it had been previously cycled a number of times. They observed that the FR then

fell below one with considerable AE threshold counts and some high amplitude AE events occurring during at least the next three additional proof cycles. Additional research needs to be done in this area to quantify the FR versus cycling load level and severity of induced damage compared to previous strength of the composite. Another study could be done concerning the changes in the FR for each cycle after damage as a function of the same variables.

Three variables which must be understood are the effect of test rate, time of hold at peak load, and time at rest before the next cycle. These variables are also certainly related to the percentage of failure level of the proof cycles. Rotem and Baruch (1974) reported some work on the effects of successive proof cycles with and without holds at the peak loads. Conlisk and Fowler (1977) showed that for a proof to a certain load level that, if the load was held until the AE stopped, then the FR was ≥ 1 and if there was no hold at the peak, then the FR was <1. This result was investigated as a function of proof level percentage of failure level by Fowler and Gray (1979) (see figure 4.7). Fowler and Scarpellini (1980) reported FR<1 without having to hold a composite in the unloaded condition if the previous load cycle was close to the ultimate load level. Thus the need for the hold at rest is also dependent on load level of the proof cycle. With respect to test rate Guild et al. (1980) and Phillips and Harris (1980) reported differing cases of AE dependence on strain rate. For a 0/90 non-woven composite, they found the number of AE events did not depend on strain rate. But for chopped-strand mat/polyester an increase in strain rate of one order of magnitude resulted in a four-fold increase in number of AE events. They conjectured that the increase in AE

events was due to increased matrix cracking since the matrix did not have time to viscoelastically relax at the higher test rate. These results indicate that test rates could also have an effect on the FR, and that studies need to be carried out in this area.

Beginning with the earliest reported Felicity effect studies, the fact that FR decreases with increases in the proof level was established [See Fowler (1977) and Fowler and Gray (1979)]. Tao and Gao (1982) recently showed extensive statistical results for the Felicity effect as a function of percentage of failure level. They included in their study the addition of amplitude distributions for each of these proof cycles. They observed that as the FR decreases the AE amplitudes up to the previous proof level increase more dramatically as a further indication of impending failure (see figure 4.8). This result implies that a more sophisticated FR could be defined based on amplitudes of the AE events that occur prior to reaching the previous peak load.

Some studies have looked at the effects of material on the FR or the effect of failure mechanisms. Fowler and Gray (1979) showed that the FR dependence on proof level is altered if the fiber volume percentage is changed. At a given percentage of the ultimate load the sample with the higher fiber volume has a lower FR. Crivelli et al. (1980) briefly studied the Felicity effect as a function of load level and angle of the plus/minus plys. This study is interesting because with different angle plys the dominant failure modes change. The study was too brief to come to firm conclusions. Hull et al. (1981) studied the Felicity effect on glass/polyester filament-wound pipe loaded in two different modes. For hoop loading they found $FR<1$ for all load levels. For combined hoop and axial loading $FR \geq 1$ for low load levels

and FR<1 at higher load levels. These results indicate that these are fruitful areas for study. The determination of the dependence of FR on the AE mechanism seems to be a most important study area.

Two other reports should be mentioned. DeLacy and Dharan (1982) reported on whether the FR=1 for temperature induced loads in composites. They concluded that the temperature at which new AE begins does not represent the previous extreme temperature due to the effect of the viscoelasticity of the matrix. Lingenfelder (1974) and Weyhreter and Horak (1978) both reported (probably the same work) that FR ≥ 1 for a subsequent compression load cycle after an original tension cycle.

There have been comparatively few attempts in the literature to explain the physics of the Felicity effect. Tutans and Urzhumtsev (1971) suggested that pull-out was not a key factor contributing to the FR<1. Fowler et al. (1979) stated that the Felicity effect is a measure of the total amount of damage and that the effect is related to the redistribution of residual stresses during the unload time. Since the FR increases with holds until AE ceases (i.e., more damage) compared to the FR with no hold, and since at high load levels no rest hold is necessary for the FR<1, these ideas seem to be only part of the explanation. Bunsell (1977) attributes the FR<1 to be due to the fact that on unloading, the matrix goes into compression such that to reach the same overall stress on the next load cycle the fibers have to be stressed further thus leading to more fiber breaks and AE. Tao and Gao (1982) derived an expression relating the FR<1 to the effective reduction in cross-sectional area which results on unload due to a redistribution of stress and consequently new AE on reloading.

It seems to the current writer that some key experiments are needed to delineate the causes of the AE which leads to the FR<1. Variables which need to be examined are: 1) matrix viscoelasticity, 2) time dependent fiber properties, 3) friction in damaged areas, 4) residual stresses, 5) matrix elasticity, and others.

Development of NDE With AE

This section deals with development of NDE on tensile specimens or specimens other than real parts or structures. The first result of significance is that almost without exception AE can detect composites with artificial flaws or damage such that the usual failure level is degraded. The following summarizes some representative work in this area.

Reference	Technique to Distinguish
Rathbun *et al.* (1971)	Source location showed most large amplitude AE came from the location of cut strands. Failure of the glass/epoxy sphere was about 25% below design level.
Hamstad (1972)	Summation of counts was used at about 33% of normal strength to pick out a flawed glass/epoxy cylinder that failed at about 70% of usual mean failure level.
Hamstad (1973)	Summation of counts was used to pick out at about 50% of normal strength a

	flawed Kevlar/epoxy cylindrical vessel which failed at about 85% of usual mean strength.
Hamstad and Chaio (1975)	Summation of counts to pick out a flawed Kevlar/epoxy strand at about about 40% of normal strength level for a strand that failed at about 80% of normal.
Becht *et al.*(1975)	Distinguished flawed tubes from unflawed by AE at lower stresses and more AE events.
Pollock and Cook (1976)	Using flawed samples of glass/plastic found that the FR<1 occurred for a proof to about one-half the residual strength.
Rotem (1978)	a) Showed summation of counts detected, at a low percentage of failure, an artificial delamination in unidirectional E-glass/epoxy *even* though tensile strength was not degraded. b) Also used same technique to distinguish specimens of E-Glass and Graphite with cut bundles that do effect the tensile strength.

	c) Correlated stress to reach a fixed number of counts and the failure stress for composites whose fibers were damaged during manufacture to create a wide distribution of failure strengths.
Williams and Lee (1979)	Detected interlaminar flaws of backing paper by three ways during tension: i) The flawed samples had about 50% more counts to proof to about 50%, ii) Higher amplitudes in flawed samples, iii) Slopes of amplitude distributions got farther apart for flawed vs. unflawed with increasing proof level.
Williams et al. (1982)	Flawed tensile samples by transverse drilled holes or V-notches: i) For sheet moulding compound (SMC) of two different percentages of chopped fiber developed a simple correlation between the number of AE events or counts during a proof to 40% and the actual tensile strength. The correlation was independent of flaw type, ii) Stress delay (i.e., the stress to reach a fixed total of AE events or counts) correlated for both SMC's (see figure 4.9) as well as

XMC (with continuous fibers). Noted that, for chopped systems, AE correlations were easier to see. Also specimens with continuous fibers had much more AE than chopped systems and for these even the proof test of unflawed samples had a lot of AE.

For specimens without a deliberate flaw or damage the techniques used above have not been nearly as successful particularly for composites with continuous fibers and which do not have a significant loss in strength. The problem seems to be that of technique rather than an inherent lack of necessary information being contained in the AE signals which are generated when the specimen is loaded. As was pointed out in Part 2 the main difficulty is that many composite specimens emit a lot of AE when they are loaded. Most of this AE is generated at random locations and has little to do with the eventual failure of the part. There are two fundamental problems. First, lack of ability to do source location on a routine basis in composites. This means that it is not possible to distinguish random AE from AE due to growing flaws. Second, the large signal propagation losses in composites. This means that it is difficult to determine the severity of the AE which is recorded. Several researchers have reported a lack of success primarily due to these problems which are more acute in uniformly loaded tensile samples. Hamstad and Chiao (1975) pointed out that they could not use summation of counts to order the failure strengths of strands of Kevlar/epoxy which failed within the normal distribution of

strengths. They attributed this to the fact that the AE system was recording AE from a series of flaws in each strand rather than from the individual flaw which controlled the failure. Rotem (1978) saw a similar result in concluding that the statistical distribution of strength could not be evaluated with AE.

Results might be expected to improve if the high stress region was localized in the test sample. In this case most of the AE events originate at the same location with respect to the sensor and the number of random AE sources and growing flaws is greatly reduced. For this type of situation Graham and Elsely (1977) correlated the ultimate failure load for graphite/epoxy specimens in four-point bending with the initial slope of the amplitude distribution for the first 500 emission events. These samples had only a small length of reduced section. Similar success was obtained by Sherer and Ashley (1981) who used three-point bend specimens, which limit the region of high bending stresses. They found a correlation of both the number of AE events on the first proof cycle (to 25% of the normal failure load) and the second proof cycle with the ultimate failure level of HMC. They stated that the first cycle correlation was better, since it had more AE events and thus the results could not be as influenced by a few random events as the second cycle. But, even with the limited volume subjected to high bending stresses, the correlations had some scatter. That is, some high AE event specimens had high failure loads. Of great significance though, was the fact that AE picked out all the bad parts (low failures), i.e., no low failures had low AE event counts during the proof cycles (see figure 4.10). They attributed the large event counts in good parts to be due to these parts having active flaws at

other than the high stress locations. Also of interest in this work was data that the two-cycle proof test did not damage the samples such as to lower their eventual failure level. This result was shown by comparing failure distributions for proofed and non-proofed specimen sets.

Other researchers have reported some success in correlating AE and failure levels. In most cases this was due to some specimens having low failures or use of more sophisticated techniques of AE data analysis. It is also possible that some of these successes would be failures if larger sample sizes were tested. Some of these results are summarized here with brief comments.

Reference	Comments
Detkov (1976)	Correlated the load at which the count rate reached a fixed value with the failure level.
Weyhreter and Horak (1978)	They used a deviation in slope of cummulative counts vs. load curve to predict ultimate strength. Also used total counts for a proof to about 63% of normal failure to predict failure based on a correlation developed with flawed parts.

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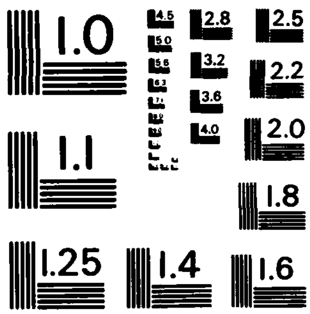

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Phillips and Harris (1980)	Observed for chopped-strand mat (CSM)/polyester that low failures compared to high failures have more events and higher amplitude events.
Djiauw and Fesko (1980)	Showed a correlation of a specially defined "energy" (based on counts and peak amplitude of events) with fatigue life for compression moulded XMC beams tested in three point bending.
Phillips *et al.* (1982)	Showed on CSM tensile samples, by comparing amplitude distributions for certain load increments (by a standard chi square test), that they could statistically distinguish a sample which failed about 20% below the mean strength based on AE from a proof to less than 50% of the normal mean strength. They also showed some indication that the number of AE events over a range of amplitudes is an indicator of specimen quality (see figure 4.11).

In summary, this writer believes that research needs to be directed to solve the two major problems of signal propagation losses and source location for composites. The financial pay off in overcoming these problems would be very high for NDE of composites.

Amplitude Distributions

The area of amplitude distributions has resulted in some controversy in the AE literature. One aspect of amplitudes that has gained wide acceptance is the concept that the higher amplitude AE events appear near failure or for flawed composite samples. Pollock and Cook (1976) observed for a pre-cycled specimen in bending upon introduction of a saw cut that high amplitude AE appeared for the first time in the next load cycle. Conlisk and Fowler (1976) clearly observed that higher amplitude AE events appeared near failure. Wolitz et al. (1978) noted for a flawed sample at about 94% of failure the amplitude distribution changed due to the appearance of high amplitude AE events. Ryder and Wadin (1979) noted in fatigue testing that only near failure did events greater than a certain amplitude appear.

The controversy with respect to amplitude distributions centers on the association of peaks or ranges of amplitudes in the distribution with particular AE source mechanisms. This concept is based on the idea that the source mechanism of a particular AE event can be determined from the value of the measured peak amplitude. A number of reports have made this claim. Ahlborn et al. (1973) distinguished fiber failures (taken to be the highest amplitudes) from delaminations by differences in the slope of the amplitude distribution. Wadin (1978) obtained an amplitude distribution with two peaks for a bend test of hand lay-up, random-orientation, chopped-strand mat. For a

glass/polyester sample filament-wound including one ply of surface mat, he obtaining an amplitude distribution with three peaks. From low to high amplitude, these peaks were respectively associated with matrix crazing (cracking), fiber-matrix debond, and fiber breaks (see figure 4.12). Wolitz et al. (1978) distinguished fiber failures from matrix and other failures since the fiber failures were about 20 dB higher in peak amplitude than other AE events. Eikelboom (1979) found three distinct peaks in amplitude distributions. With his AE equipment these were 31, 43, and 52 dB. He respectively correlated these with matrix cracks, fiber matrix delamination and fiber cracking. This correlation was developed based on the load level where the peaks grew and on which peaks appeared in various off-axis tests (e.g., at the highest off-axis angles matrix cracking predomimates, while at lesser angles delamination also appears). Ryder and Wadin (1979) during fatigue tests recorded with their instrumentation only events <45 dB prior to any delamination. During delamination they saw events which were >50 dB. Not until near failure did they observe events >65 dB. Phillips and Harris (1980) observed during tensile testing of CSM that two peaks appeared in their amplitude distribution, which implied two mechanisms were operating (see figure 4.13).

The question of when peak amplitude can be used to identify source mechanisms in composites has not been unequivocally answered. To date it has not been possible to physically verify the mechanism of each AE event and then compare the peak amplitude that was obtained. To do this is not an easy task. Several researchers have pointed out potential difficulties with source identification by amplitude. Hamstad (1979) pointed out that large signal propagation losses make it

difficult to use peak amplitude to determine the criticality of AE sources in composites. Guild et al. (1980) pointed to their expectation that the energy released depends on both the failure mechanism and the mode of deformation applied. They also pointed out that distributions taken from 0^{o} and 90^{o} tests of unidirectional samples did not behave as expected if it was assumed that fiber failures have the highest amplitudes. Graham (1979) presented the idea that, due to statistical variations within classes of AE sources, there are overlaps in amplitudes such that it is difficult to uniquely define the source mechanism for each AE event based on peak amplitude alone. Phillips and Harris (1980) on the basis of amplitude distributions obtained from several types of glass laminates concluded that the AE source mechanisms can't be determined on the basis of amplitude distributions alone. Hamstad (1981) pointed out that in addition to a dependence on source mechanism, the peak amplitude out of an AE sensor depends on propagation distance, propagation paths, modes of propagation, size of the source mechanism, and the superposition of more than one wave packet. In this writer's opinion, there is still significant research to be done in defining the use and limitations of amplitude distributions for source identity in composites. With multi-channel modern computer based AE equipment much of this research can be done quite easily by comparing the characterization of individual AE events by several sensors located both near and far from sources of different mechanisms.

The analytical description and comparison of amplitude distributions has also drawn some recent attention in the AE literature. Graham (1980) noted the need to use an extreme value function rather

than a power law to provide an analytical fit of amplitude distributions. He also proposed a decomposition of an amplitude distribution which cannot be described by a single straight line into several different distributions (see figure 4.14). He provided some justification for this based on the fact he obtained the same modal and shape values for the sub-distributions for tension and compression tests of both wet and dry samples. Phillips et al. (1981) suggested the single b-parameter (basically the slope of the distribution) is not sufficient to characterize typical composite amplitude distributions. They used two different statistical approaches to determine if two different distributions differed significantly. They concluded that both approaches led to improved discrimination between distributions. This writer expects additional work in these areas to be fruitful subjects. One potential need is to couple AE amplitude distributions with load level so that the fundamental connection between the driving force (which causes AE) and the resulting AE events is not lost.

Frequency Analysis and Bandpasses

The use of frequency spectra to sort out AE source mechanisms in composites is not as well developed as is amplitude distribution. One difficulty is that in most cases it is not possible to obtain frequency spectra on a real time basis. Hence, statistical samples of spectra for association with particular source mechanisms are rare. Another difficulty is that the association of a particular AE event (with associated spectrum) and a physically verifiable source mechanism is not an easy task in a real composite. Only in special model composites with one or only a few fibers can this be done. Hence, the more extensive modification of the signal in propagation in a real composite

has not been a factor in many experiments. In this section we will first briefly summarize results in the literature where certain spectra were attributed to certain source mechanisms. Then we will discuss some of the reasons put forth as to why spectrum analysis is not easy in composites. Finally we will briefly mention other results of interest.

Reference	Result
Buhman (1975)	Showed two distinct spectra (and time domains) for fiber and non-fiber events in both model composites (e.g., samples with few fibers) and composite tubes (see figure 4.15). The spectrum for fiber fracture was similar to the theoretical spectrum from an impulse. The non-fiber spectrum was similar to the theoretical one from a transient process with at least one resonance. Band pass for this work was from less than 14 kHz down to a few hertz.
Wolitz <u>et</u> <u>al.</u> (1978)	A high frequency spectrum was associated with fiber fractures and a low frequency spectrum was associated with matrix events.

Henneke (1978)	Indications of ability to distinguish two failure modes by spectra over 0-300 kHz range. Fiber failures were associated with a larger number of frequency peaks and a broader and flatter envelope of their spectrum than for matrix cracking. Specimen design limited origin of AE events to a small flawed region, so that the path to sensor and position of source with respect to the specimen does not vary greatly.
Govada <u>et al.</u> (1981)	In tension tests of boron carbide coated boron fibers in titanium they observed three distinct spectrums and time domains.

A number of experimenters have pointed out potential difficulties in using spectra for source identification. Speake and Curtis (1974) determined that AE spectra depend on both material type and test specimen geometry. Hamstad and Chiao (1976) observed for a repeatable source (glass capillary breaks) at different locations on the specimen that spectra and time domains both varied. Graham (1977) stated that the spectral content of individual events in graphite/epoxy were much more variable than for other non-composites which he had previously studied. Russell and Henneke (1977) observed that the natural

resonances of the sensor and specimen determined the frequency content of spectra. Further, that spectra from unidirectional samples gave some trends with respect to an association of spectrum and source type, while no trends were observed for complicated laminates.

Graham (1977, 1978, 1980) has tried a number of more sophisticated ways with varying success to attempt to correlate spectra with AE source types. One attempt used a seven-dimensional space (seven discrete frequency amplitudes for each AE event) to attempt to classify events. This approach was not fruitful in general, except that certain spectral types were observed to first appear in association with load drops. Another approach correlated the ratio of the amplitude at 56 kHz to the amplitude at 560 kHz. Events could then be classified by: i) ratio = 1, implies a broadband event; ii) ratio <<1, implies a high frequency dominated event; and iii) ratio >>1, implies a low frequency dominated event. He observed some distinct differences in the typical ratio at changes in slope of the load vs. time curve for a tension test of wet graphite/epoxy, e.g., the typical ratio was >>1 at the point where delaminations were expected to start (see figure 4.16). Finally, Graham plotted a distribution of number of events vs. ratio of amplitude at 56 kHz compared to 560 kHz. He then decomposed these distributions into sub-distributions. He found more sub-distributions were needed than for the corresponding amplitude distribution. This result raised questions about the approach.

Two other references should be mentioned in this section. Scott (1977) observed while monitoring tension tests of unidirectional boron/aluminum that for different frequency bandpasses (different AE sensors were used for each bandpass) the shape of the count-rate vs.

strain curves was different for the two bandpasses for tests at 0° while the curves were the same for off-axis tests at greater than 60°. He suggested this result indicated that the dominance of certain AE source mechanisms could be determined by different bandpasses. An alternative explanation could be that the two AE systems had different sensitivities and the change was due to amplitude differences of the AE [Sims and Gladman (1979) showed changes in gain can change the shape of summation of counts vs. load curves]. Egan and Williams (1978) attempted to distinguish off-axis tests at 0°, 10°, and 90° with $+45^{\circ}$ laminates. They subtracted the background noise spectra and then averaged the spectra for all events for each specimen. Using a paired-sample t approach they distinguished the latter three specimen types from each other at 0.74 level of significance.

In summary, source identification by spectrum seems to be still in an early state of development. Considering complexity of this area and until AE systems are available which will provide spectra at a rapid rate, this area of research may not have as high a priority as other areas.

Other Techniques for AE Source Identification

Since there is just a scatter of work here, we will list the references with some brief comments. With the increased sophistication of computer based AE systems, this area of research is expected to grow rapidly in the coming years.

Reference	Comments
Green *et al.* (1964)	Attempted to use "voice prints" which gave amplitude contours in a plot of frequency vs. time as a means of source identification.
Graham (1976)	In graphite/epoxy observed three distinct ranges in AE signals when the ratio of burst duration to peak amplitude was obtained. These three ranges were: i) about 100 μ sec/volt, ii) 400-800 μsec/volt, iii) 2,000-10,000 μsec/volt.
Russell and Henneke (1977) and Henneke (1978)	Observed differences in rise time and event duration for fiber breaks (more than one fiber broke at a time) and matrix cracks (longitudinal splits in the fiber direction). For flawed samples the fiber breaks had slower rise times, longer durations, and larger amplitudes. The matrix cracks had fast rise times and less than 400 μ sec duration.

Bae *et al.* (1980)	They first tried to modelize the time domain envelopes. This did not result in a significant clustering and the pattern recognition algorithm did not converge for any set of parameters. They next obtained the power spectral density for each event and then divided the frequency band into twenty segments and computed by integration the energy in each segment. This resulted in twenty features for each event. The twenty features were reduced to fourteen by principle component analysis. Finally, an unsupervised pattern recognition method called ISODATA algorithm was used. The result was four classes of AE events which each occurred only during specific steps in the delamination process of a composite (see figure 4.17).

General Techniques for Verification of AE Sources

Without a knowledge of the source of AE in a composite, the understanding and usefulness of the AE data is limited relative to the full potential of AE. Since composites are a very diverse class of

materials, the potential source mechanisms are numerous. Thus it is not an easy task to determine what the actual source mechanisms are as a function of stress level. The ideal situation would be the development of techniques to allow the source mechanism (as well as source location) of each AE event to be positively determined. Since this situation is still a research goal for most cases, the best that can be done at this point is to use various techniques to identify the dominant or most likely sources of AE in a composite. The most satisfying approaches are those which allow a physical verification of the dominant sources. Unfortunately, this approach is often only of use for special model specimens. And often it is never of use for real samples since it usually means destruction of the test sample. In this section we will outline different classes of verification methods which have been used. We will try to distinguish the type of composite on which the technique was applied where this seems important. The reader is advised to consult the original reference to determine the adequacy of these techniques.

I. Physical Techniques

References	Comments
Lloyd and Tangri (1974)	For short fibers Mo/Al_2O_3 used microscopy to verify matrix cracking and fiber pullout as sources.
Mazzio *et al.* (1973)	Used optical inspection (through clear epoxy) to count the number of graphite fiber failures in a model

	composite with only a few filaments.
Sims *et al.* (1977)	Used optical means to measure the number of cracks in the 90^{o} layer of $0^{o}/90^{o}$ samples tested in tension.
Pless *et al.* (1982)	Applied "deply" technique to graphite/epoxy samples. Physically counted fiber bundle fractures as well as delaminations and/or matrix cracks which extended to the edges of the specimen.
Buhman (1975)	Used leakage of gas through walls of filament wound pipe to prove first AE correlates with matrix cracks.
Mehan and Mullin (1971)	Used optical verification of fiber breaks in Boron/epoxy samples with a few filaments.

Old and Charlesworth (1976)	Sectioning and microscopy to verify strain level where metal fibers first suffered transverse cracks.
Ryder and Wadin (1979)	Visual observation of delamination during fatigue testing.
Eisenblatter et al. (1974)	Transmitted light to verify delamination area of a composite tube.
Fuwa et al. (1975)	Dissolved matrix away by acid and then used SEM to find fiber bundle fractures.
Harris and Ankara (1978)	Used polarized light to follow crack progress in double-cantilever-beam (DCB).
DeCharentenay et al. (1979)	Observed "whitening" at tip of defect corresponds to initiation of AE.
Henneke and Jones (1979)	Chemically etched aluminum from Boron/Aluminum to find number of broken fibers.

Harris *et al.* (1972)	Polished surface of Al_3Ni wiskers in aluminum matrix to measure fiber breaks.
Rathbun *et al.* (1971)	Burn-off epoxy and unravel glass wound sphere to verify locations of fiber failures.

II. Special Specimens to Control Sources

References	Comments
Lloyd and Tangri (1979)	Used all matrix samples to eliminate fiber sources in some experiments.
Johnson and Jackson (1982)	A very rubbery matrix, urethane, so only sources were fiber failure or interfacial debonding in a short fiber composite. Also used fibers below critical length to eliminate fiber failures.
Scott (1977)	Used various on- and off-axis tests of unidirectional samples to change dominant source mechanisms.
Buhman (1975)	Model specimens to provide fiber sources: a) a fiber bundle with

	epoxy, b) thin-walled pressure vessel with elastomer matrix; to provide matrix sources: a) transverse loading of unidirectional samples, b) rubber fibers with rigid matrix.
DeCharentenay and Benzeggagh (1980)	Special mode I type sample to create delamination sources.
Fuwa _et_ _al._ (1975)	Special specimens to identify fiber failures: i) fully cured samples, ii) gage section not cured but cured under tabs, iii) gage section no resin but cured resin under tabs.
Hamstad (1972)	DCB with and without fibers with polarized light.
Harris and Ankara (1978)	DCB's: a) No fibers, b) Few fibers, c) Different fiber angles, d) Fibers coated with release agent. Above conditions to vary mechanisms: i) matrix cracking, ii) fiber failures, iii) fiber-matrix debond, iv) fiber pull-out.

Dingwall and Mead (1975)	Vary span,(s), to thickness, (d), in three point bend to obtain different failure modes: i) s/d=5 interlaminar shear failure, ii) s/d=7.5, 10 flexure failure.
Crivelli _et_ _al._ (1980)	Vary plus/minus fiber angles to vary dominant stresses in angle plys.

III. Other Techniques

References	Comments
Ahlborn _et_ _al._ (1973)	Break in slope of stress strain curve corresponds to delaminations.
Swindlehurst (1978)	X-ray for metal fiber/copper composite shows fiber breaks; also load drops occurred at fiber fractures.
Bailey _et_ _al._ (1978)	Matrix cracking verified by x-ray enhanced with tetrabromoethane.
Fitz-Randolph (1971)	In boron/epoxy during three point bend tests used electrical resistance change to measure broken filaments.

Grandemange and Street (1975)	Radiography to verify fiber breaks in boron/aluminum.
Stone (1978)	Electrical resistance of graphite/epoxy specimens to measure fiber breakage (see figure 4.18).
DeCharentenay *et al.* (1980)	C-scans used to verify delaminations correspond to start of AE in short beam shear in fatigue. Also compliance increases just after AE begins.
Kim and Hahn (1979)	Cracking under strain gages resulted in a jump in strain corresponding to AE.

IV. Analytical Work to Relate AE to Sources

Reference	Comment
Swindlehurst and Engel (1980)	Energy available from single fiber fracture in an infinite matrix.
Rotem (1977)	Quotes reference on the difference of stored energy before and after fiber fracture.

Tetelman (1972)	Reports other's results on energy released at fiber fracture.
Henneke and Jones (1979)	Analytical inversion to obtain cummulative damage vs. strain.
Robinson (1972)	Model for AE dominated by fiber fracture vs. load.

Figure Captions

Figure 4.1 AE bursts with large changes in energy, but only a small change in peak amplitude. Vertical and horizontal scales the same for all three bursts [149].

Figure 4.2 Extraneous grip noise identified by large amount of AE after reinstall compared to reload AE [156].

Figure 4.3 Data shows signal propagation losses are much greater for 100 kHz high pass than 10 kHz high pass [236].

Figure 4.4 Local flaw growth above 20 MPa is not apparent when AE data is processed over high frequency bandpass of 200-300 kHz [152].

Figure 4.5 Photograph of waveguide used to monitor AE in proof test of pressure vessel [156].

Figure 4.6 Photograph of test fixture and lead breaker for calibration of AE acceptance proof test [153].

Figure 4.7 Data show Felicity ratio depends on load level and fiber volume [73].

Figure 4.8 AE data for repeated loadings, including event amplitude data for the original cycle to a given load, e.g., 10-1 and amplitude data to load level 10 for the second cycle 10-2 [290].

Figure 4.9 Correlation of cummulative AE counts stress delay from proof and eventual failure strength [304].

Figure 4.10 Correlation of flexural strength and number of AE events during hold at peak load of proof cycle [262].

Figure 4.11 Distinction by AE amplitude distribution between sample with low failure strength, F = 965 Kgf, and high failure strength, F = 1200 Kgf [231].

Figure 4.12 Peak amplitude distribution showing three peaks associated with different failure mechanisms [296].

Figure 4.13 Amplitude distribution showing two peaks [229].

Figure 4.14 Decomposition of a single amplitude distribution in four separate distributions [115].

Figure 4.15 Time domains for fiber break (a) and interfiber break (b) [34].

Figure 4.16 Changes in typical ratio of amplitude at 56 kHz to amplitude at 560 kHz for AE events corresponding to load versus time curve [109].

Figure 4.17 Correspondence of classes of AE events identified by pattern recognition technique and stages in the delamination experiment (a - Stress vs. strain; b - AE count, c - the four classes, each mark is one event). Points A, B, and C identify the beginning of different stages in the delamination experiment [14].

Figure 4.18 Correlation of changes in electrical resistance with AE [280].

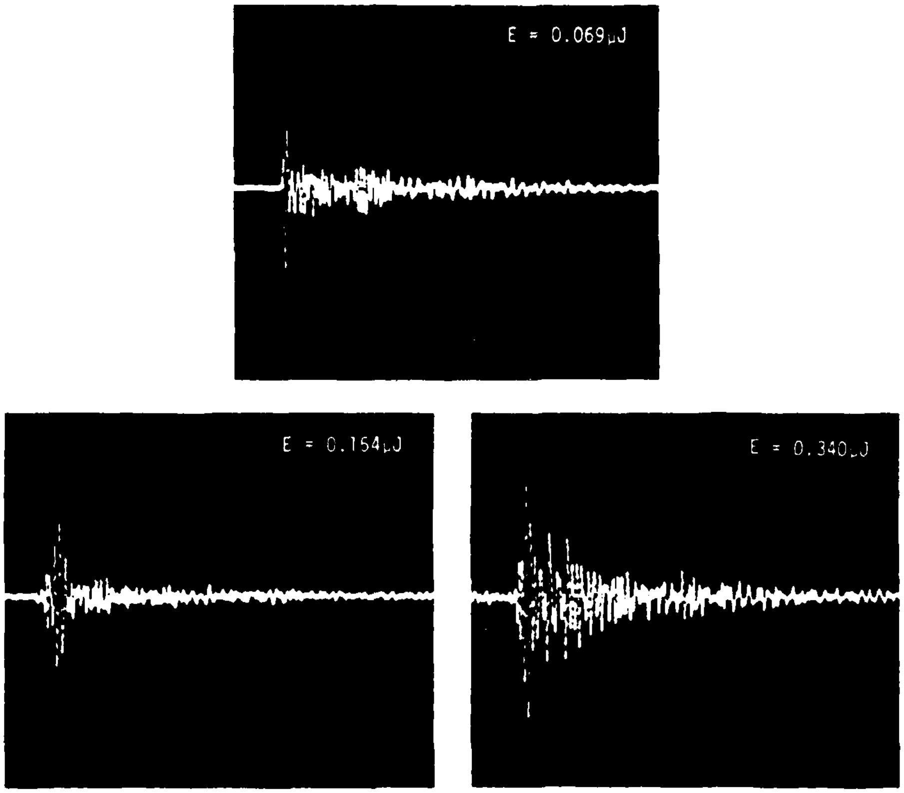


Fig. 4.1

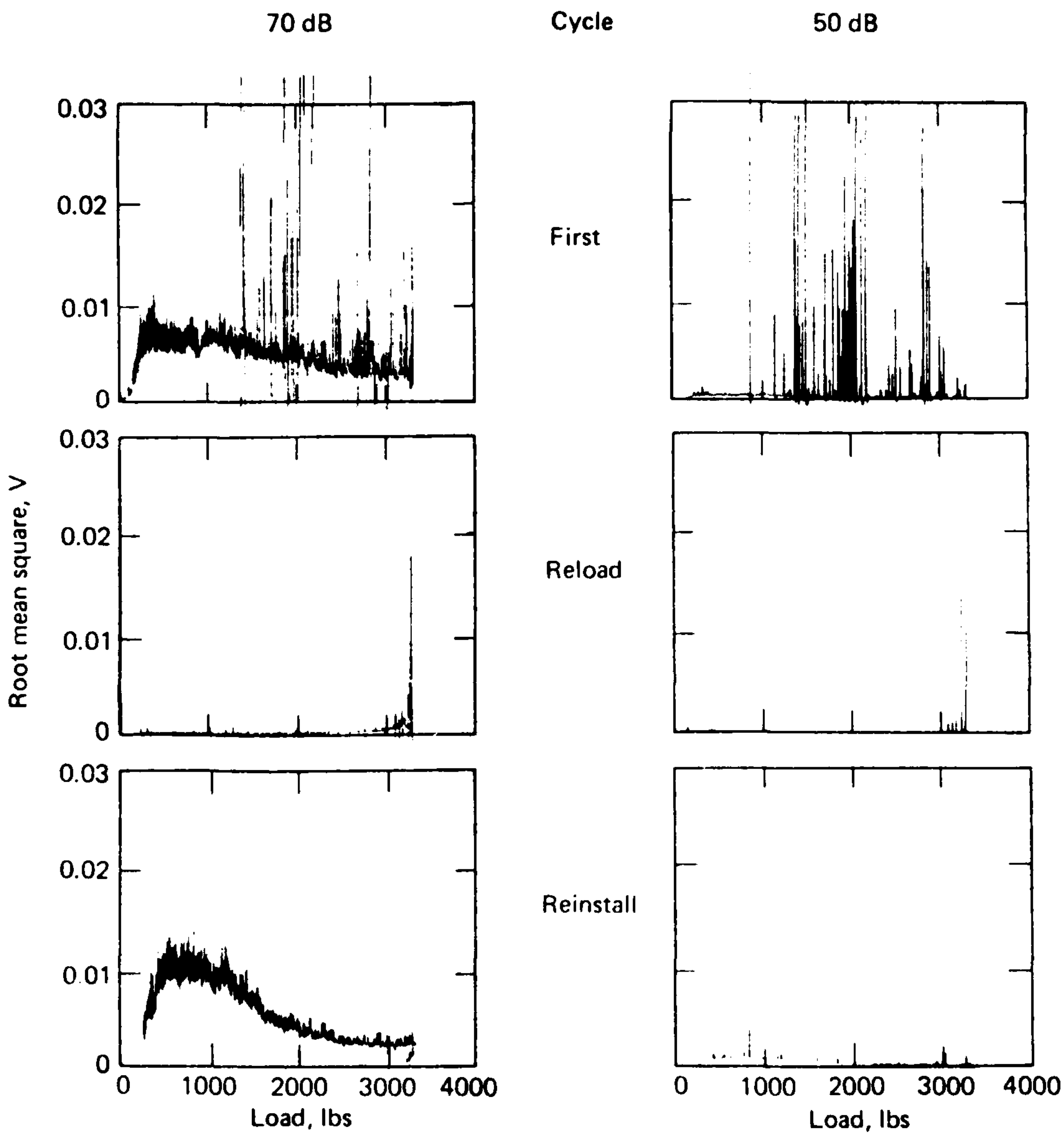
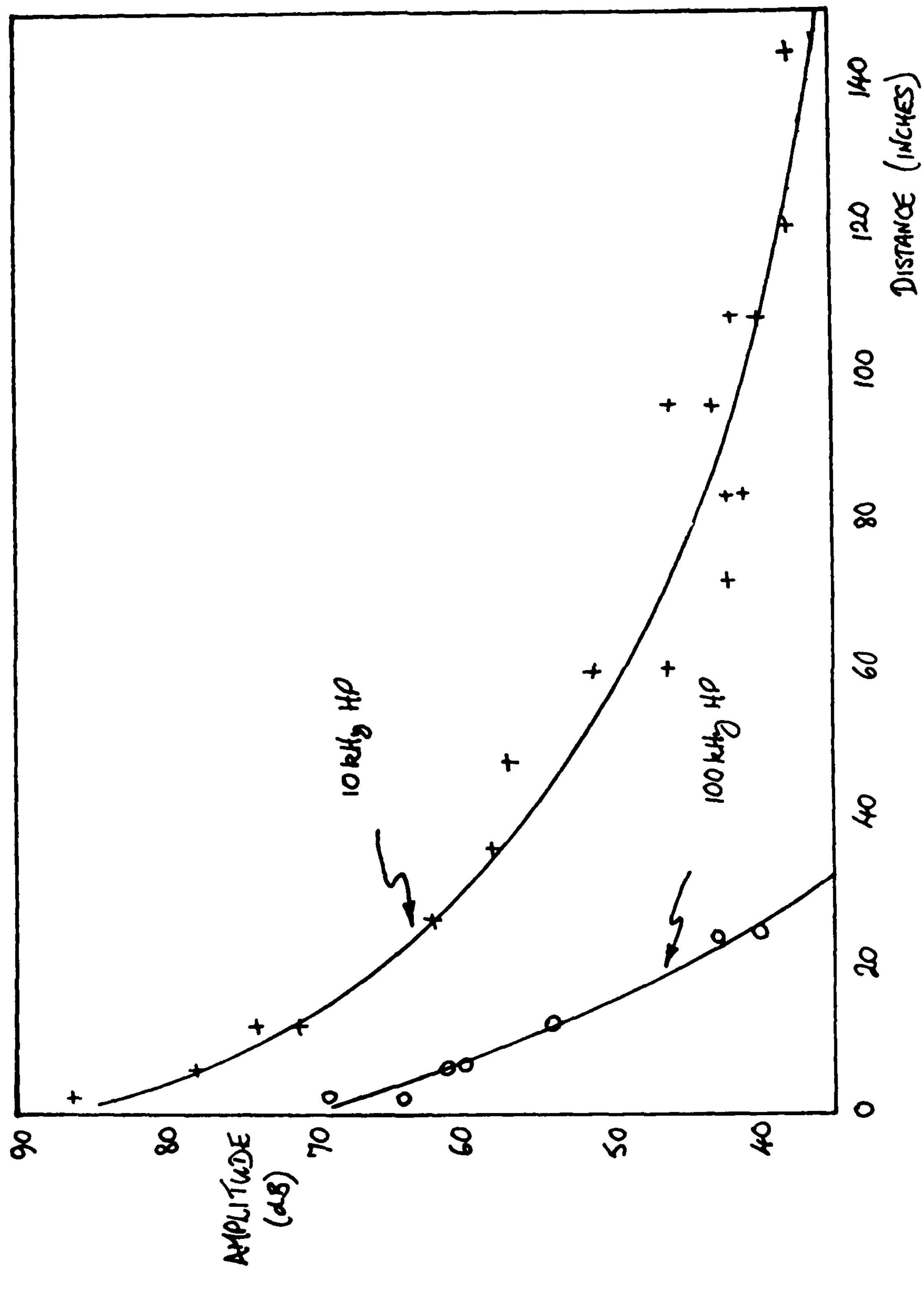

70 dB
Cycle
50 dB
First
Reload
Reinstall
Root mean square, V
0.03
0.02
0.01
0
0
1000
2000
3000
4000
Load, lbs

Fig. 4.2



AMPLITUDE (dB)
DISTANCE (INCHES)
10 kHz HP
100 kHz HP
90
80
70
60
50
40
0
20
40
60
80
100
120
140

Fig. 4.3

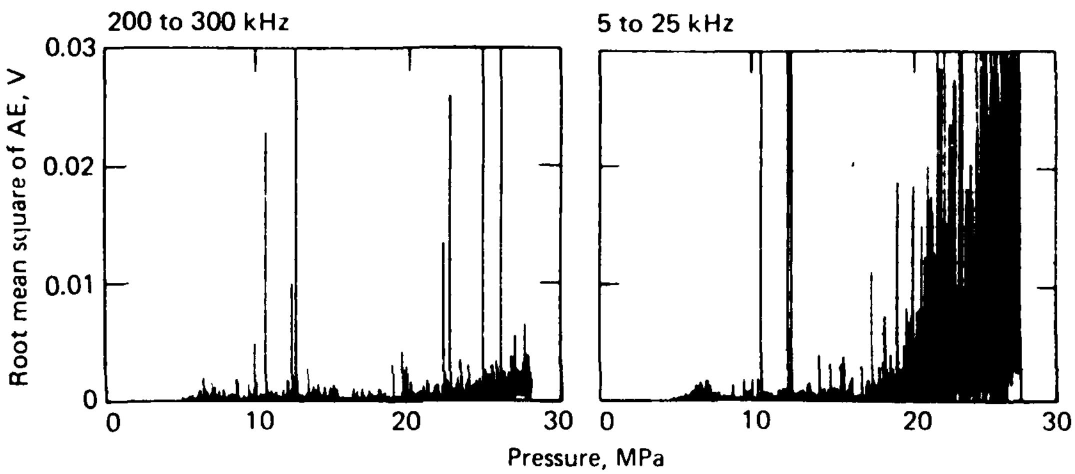

200 to 300 kHz
5 to 25 kHz
Root mean square of AE, V
0.03
0.02
0.01
0
0
10
20
30
Pressure, MPa

Fig. 4.4

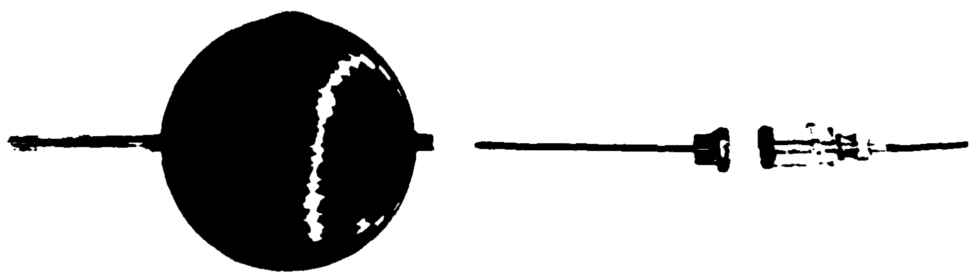


Fig. 4.5

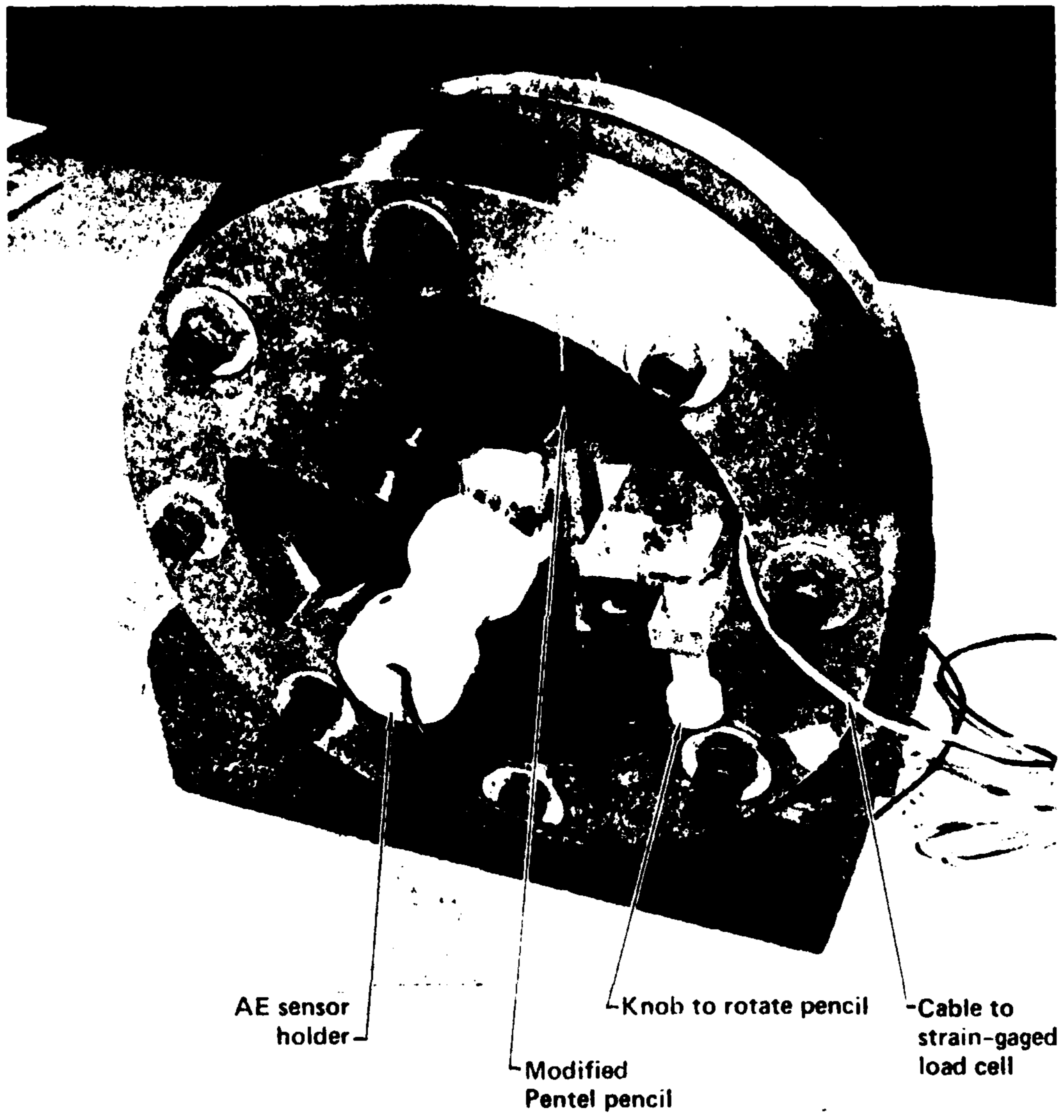
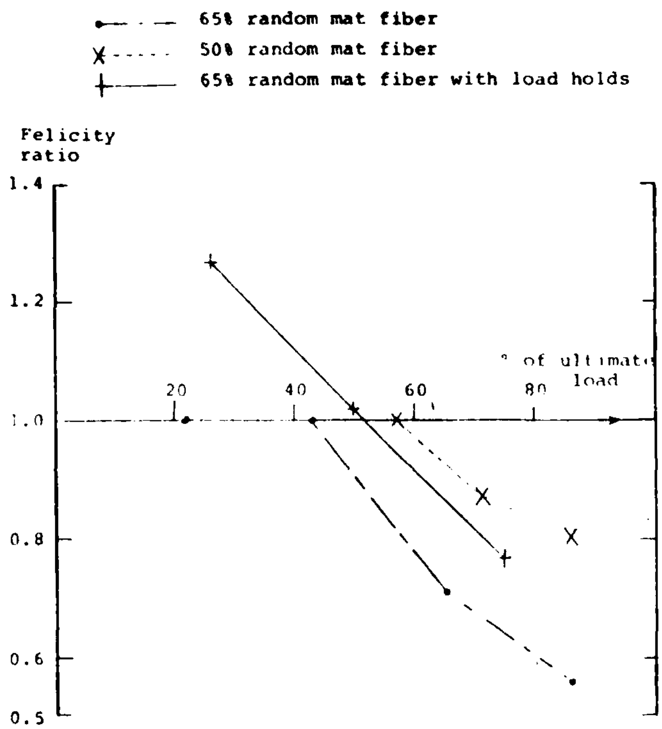
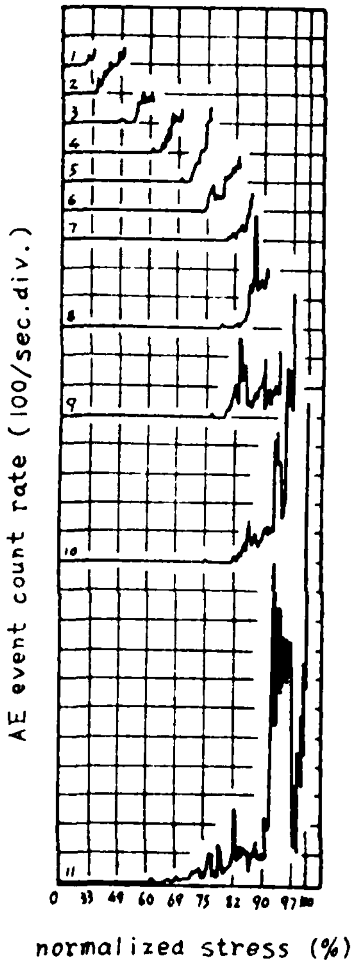

AE sensor
holder
Modified
Pentel pencil
Knob to rotate pencil
Cable to
strain-gaged
load cell

Fig. 4.6



65% random mat fiber
50% random mat fiber
65% random mat fiber with load holds
Felicity ratio
1.4
1.2
1.0
0.8
0.6
0.5
20
40
60
80
% of ultimate load

Fig. 4.7


AE event count rate (100/sec.div.)
0 33 49 60 69 75 82 90 97 100
normalized stress (%)

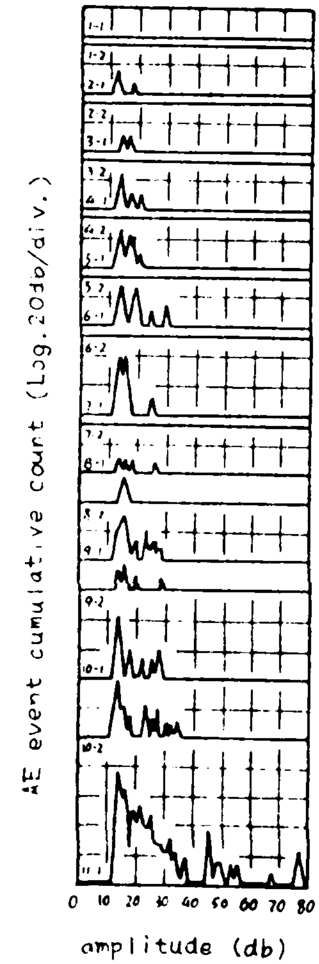
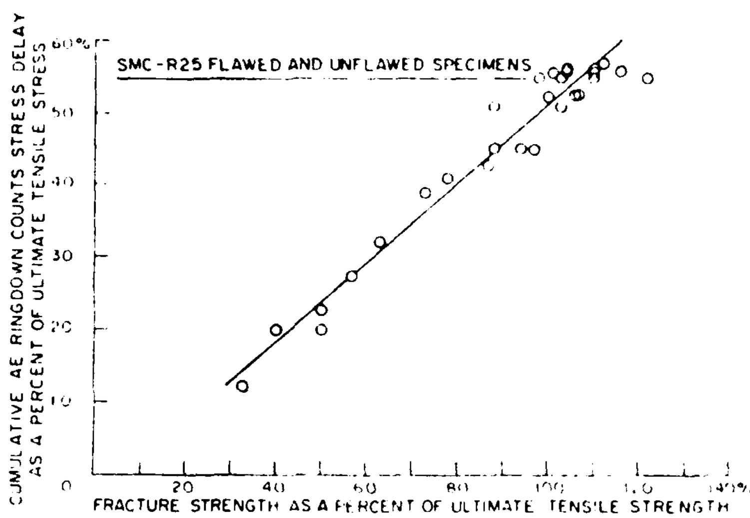

AE event cumulative count (Log.20db/div.)
0 10 20 30 40 50 60 70 80
amplitude (db)

Fig. 4.8



SMC-R25 FLAWED AND UNFLAWED SPECIMENS
CUMULATIVE AE RINGDOWN COUNTS STRESS DELAY AS A PERCENT OF ULTIMATE TENSILE STRESS
FRACTURE STRENGTH AS A PERCENT OF ULTIMATE TENSILE STRENGTH

Fig. 4.9

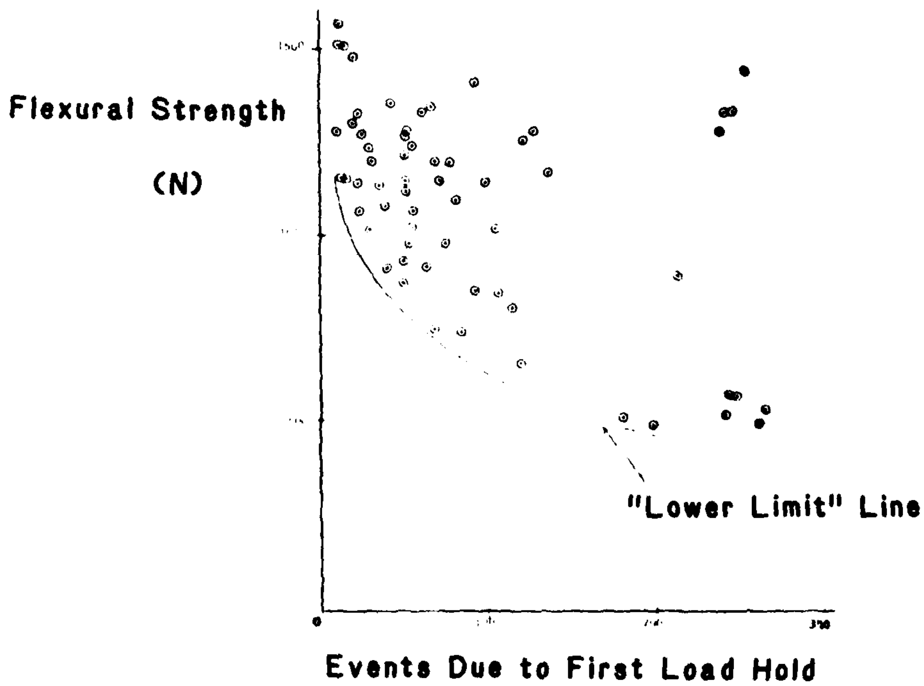

Flexural Strength
(N)
"Lower Limit" Line
0
Events Due to First Load Hold

Fig. 4.10

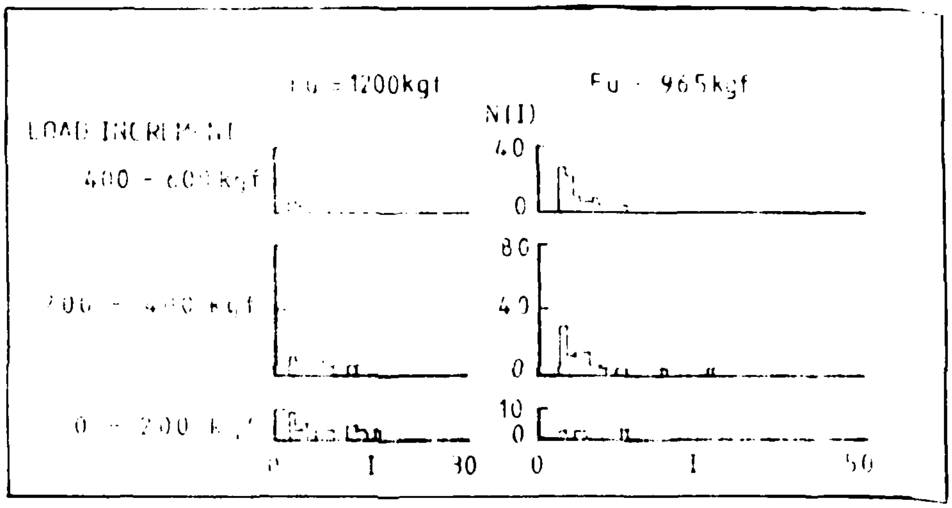

Fu = 1200kgf
Fu = 965kgf
N(I)
LOAD INCREMENT
400 - 600 kgf
200 - 400 kgf
0 - 200 kgf
40
0
80
40
0
10
0
0
I
30
0
I
50

Fig. 4.11

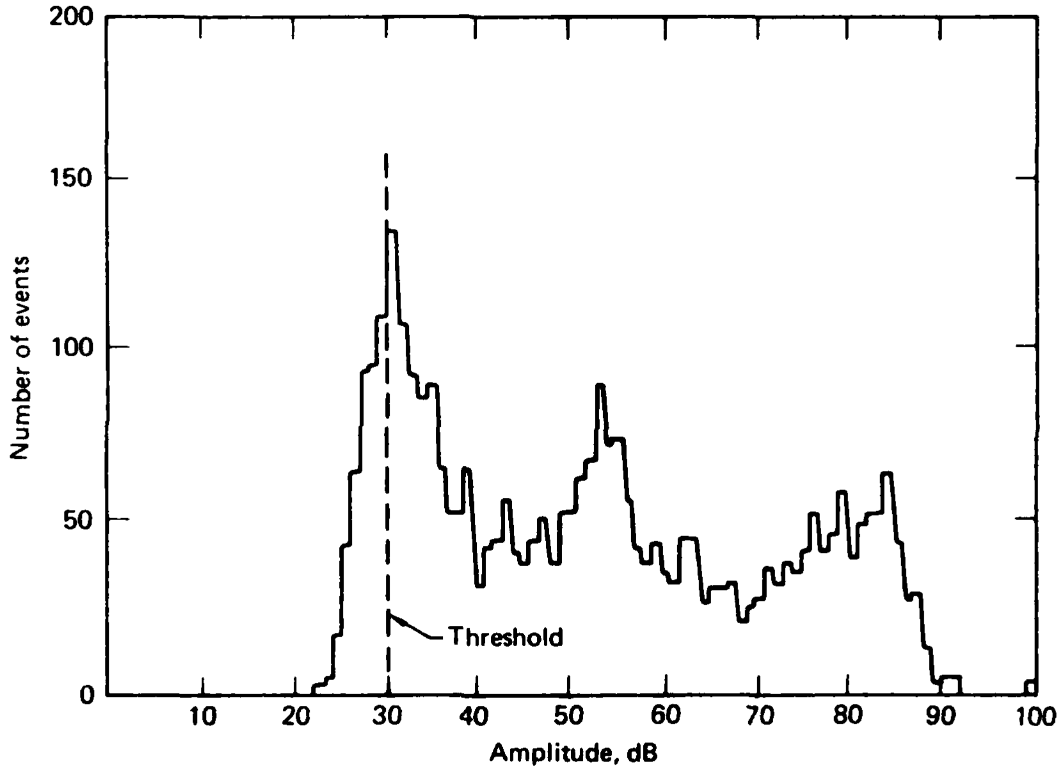

200
150
100
50
0
Number of events
Threshold
10
20
30
40
50
60
70
80
90
100
Amplitude, dB

Fig. 4.12

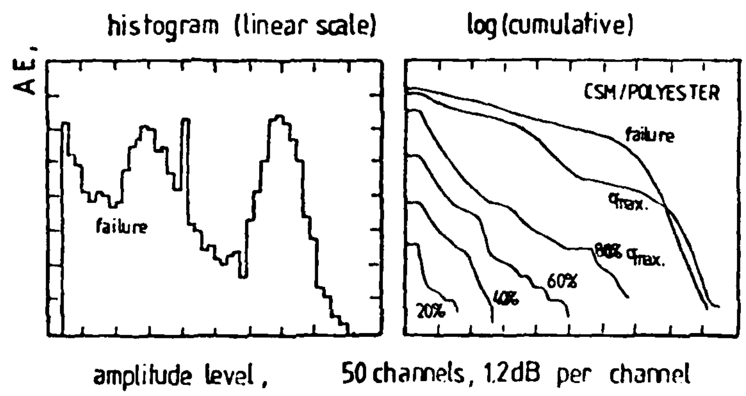
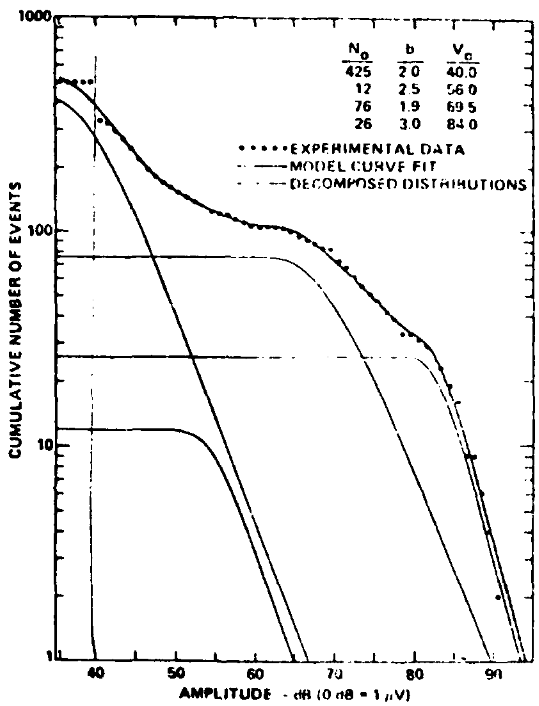
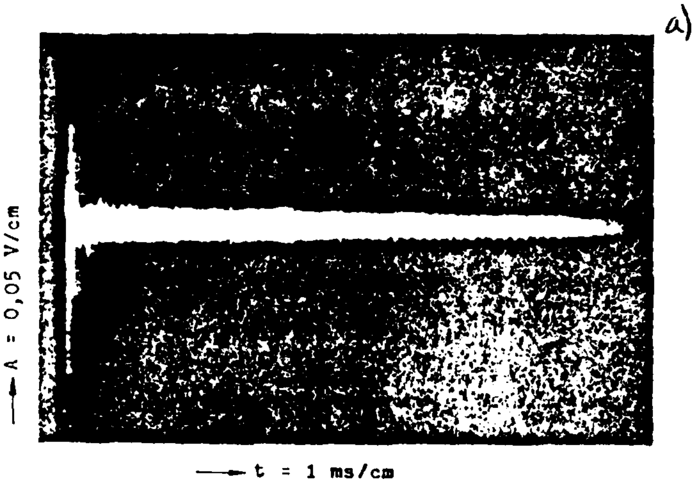

histogram (linear scale)
log(cumulative)
A.E.
failure
CSM/POLYESTER
failure
$\sigma_{max.}$
80% $\sigma_{max.}$
60%
40%
20%
amplitude level, 50 channels, 1.2dB per channel

Fig. 4.13



N_o b V_o
425 2.0 40.0
12 2.5 56.0
76 1.9 69.5
26 3.0 84.0
EXPERIMENTAL DATA
MODEL CURVE FIT
DECOMPOSED DISTRIBUTIONS
CUMULATIVE NUMBER OF EVENTS
1000
100
10
1
40
50
60
70
80
90
AMPLITUDE - dB (0 dB = 1 μV)

Fig. 4.14



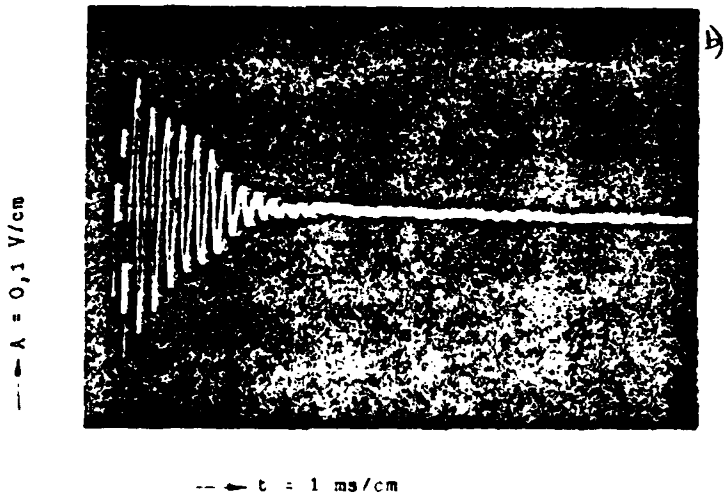


Fig. 4.15

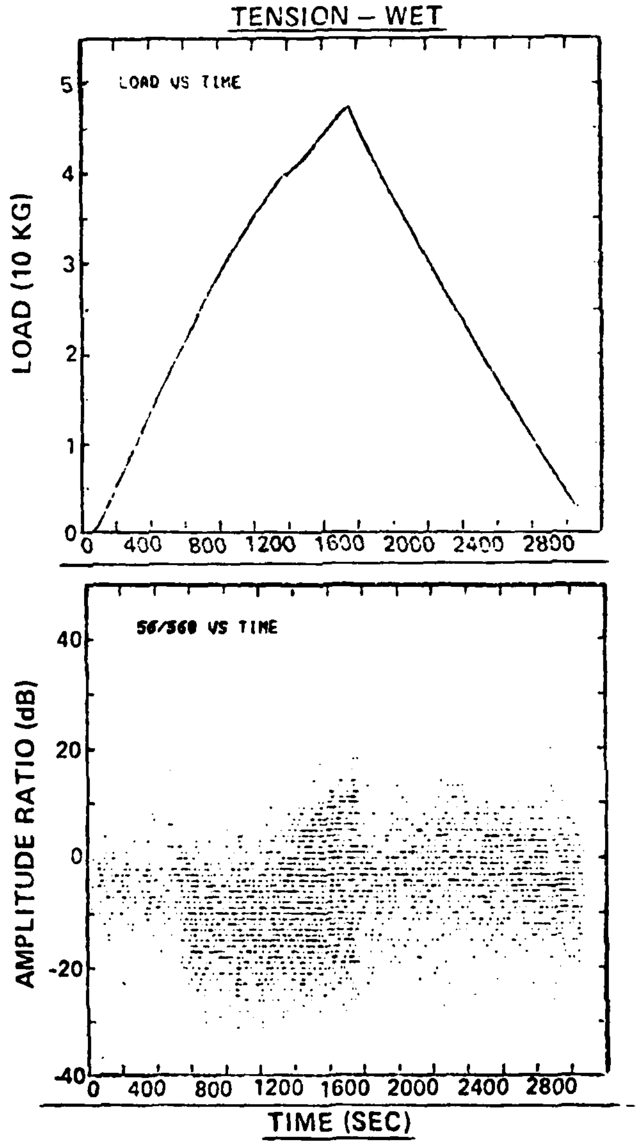

TENSION – WET
LOAD VS TIME
LOAD (10 KG)
5
4
3
2
1
0
0
400
800
1200
1600
2000
2400
2800
56/560 VS TIME
AMPLITUDE RATIO (dB)
40
20
0
-20
-40
0
400
800
1200
1600
2000
2400
2800
TIME (SEC)

Fig. 4.16

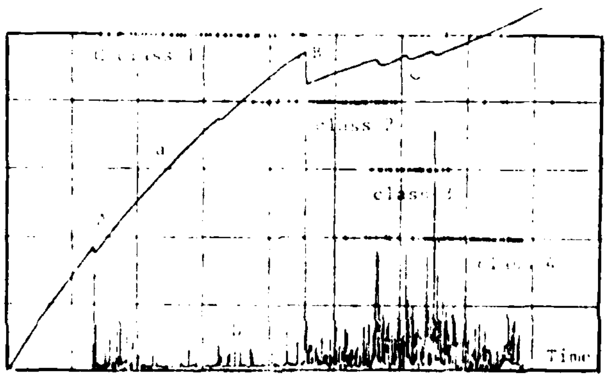


Fig. 4.17

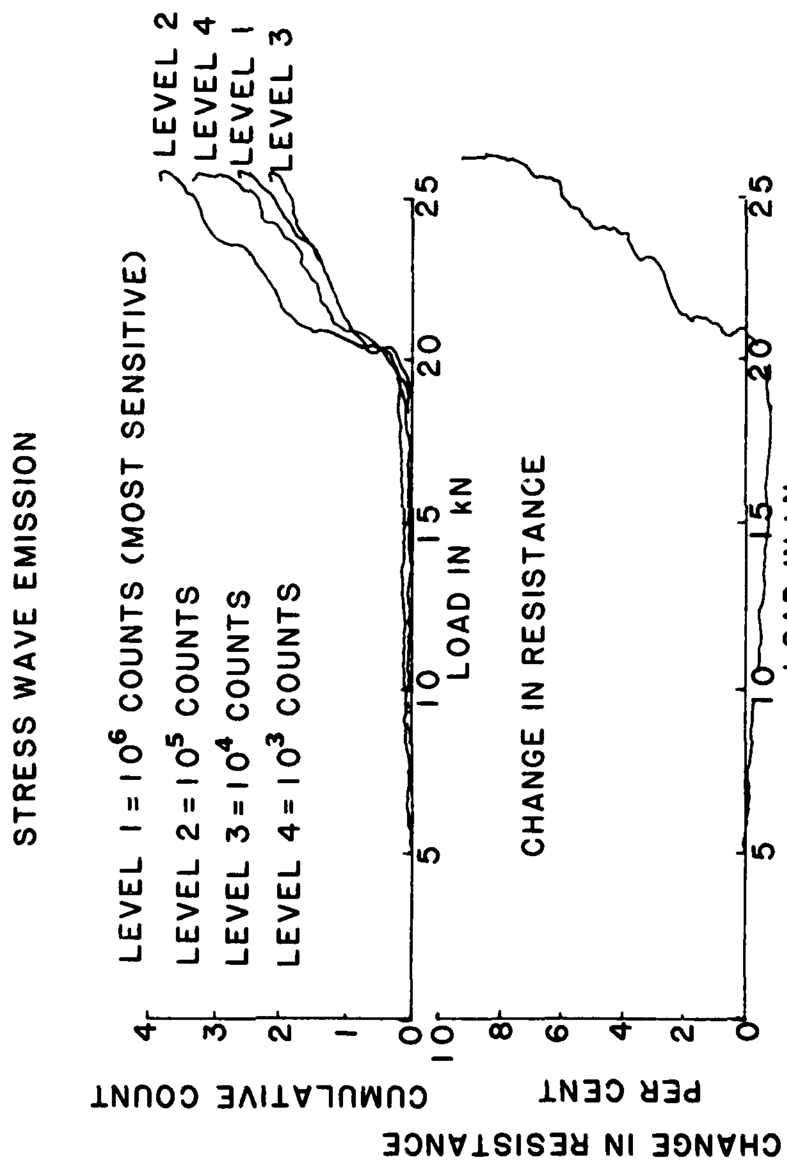

STRESS WAVE EMISSION
LEVEL 1 = 10^6 COUNTS (MOST SENSITIVE)
LEVEL 2 = 10^5 COUNTS
LEVEL 3 = 10^4 COUNTS
LEVEL 4 = 10^3 COUNTS
LEVEL 2
LEVEL 4
LEVEL 1
LEVEL 3
CUMULATIVE COUNT
0
1
2
3
4
5
10
15
20
25
LOAD IN kN
CHANGE IN RESISTANCE
CHANGE IN RESISTANCE PER CENT
0
2
4
6
8
10
5
10
15
20
25
LOAD IN kN

Fig. 4.18

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Quality Control and Nondestructive Evaluation Techniques for Composites - Part VI: Acoustic Emission - A State-of-the-Art Review, Marvin A. Hamstad, University of Denver, Colorado Seminary, Department of Physics, Denver, Colorado 80208

Technical Report AVRADCOM TR 83-F-7, May 1983, figures, Contract DAAG29-81-D-0100, D/A Project 1827119, AMCMS Code 1497.20, Final Report, August 1982 - February 1983

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Key Words
Composite materials
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Quality control
Nondestructive testing
Acoustic emissions
Damage
Defects (materials)
State-of-the-art

A comprehensive report on the subject of acoustic emission (AE) as applied to characterization and testing of composite materials and structures has been written. First, an extensive bibliography of over 300 references of the literature in this field is presented. This part includes author and subject indexes as well as a guide to the more significant literature. Second, the technical principles which must be adhered to in order to do a technically sound AE test on a composite sample are described in some detail. This part includes all aspects of standard testing and data analysis. Third, a representative survey of typical proven applications of AE to composites is presented. This survey has two basic divisions: (1) the application of AE to material studies of composites; and (2) the application of AE to quality control and/or nondestructive evaluation. Finally, a review of the progress in the research areas of AE and composites is given. This review covers the specific areas which have not yet been brought to maturity. In appropriate cases critical comments are made as well as suggestions for future work.

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